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THE SEASONAL VARIATION OF THE STRENGTH OF THE SOUTHERN CIRCUMPOLAR VORTEX

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ABSTRACT

The annual march of the strength of the southern circumpolar vortex is shown to be composed of a simple annual variation (with the maximum occurring in late winter) which dominates in the stratosphere, and a semiannual variation with the maximum at the equinoxes, which is the dominating part in the troposphere. This behavior of the circumpolar vortex is considered to be the consequence of the seasonal variation of radiation conditions and of the different efficiency of meridional turbulent exchange in the troposphere and stratosphere. It is suggested that the semiannual variation of the tropospheric vortex is an essential feature of a planetary circulation. The annual march of pressure with opposite phase values at polar and middle latitudes, can be understood as a consequence of the formation and decay of the great circumpolar vortex.

1. INTRODUCTION

Some aerological data of the Southern Hemisphere and particularly those from the South Pole (Amundsen-Scott Station) obtained during the IGY and its extension through 1959, make it possible for the first time to arrive at an estimate of the seasonal variation in the strength of the southern circumpolar vortex (in the following abbreviated: SCPV) and suggest explanations of the variations.

As a measure of the "strength" of the SCPV consider the geopotential height differences, along isobaric surfaces, between the mean values of three longitudinally almost evenly spaced stations at about 50° S. (Invercargill, Marion Island, and Port Stanley), and the values at the South Pole station. This measure seems to be the best at hand as long as reliable and complete upper-air charts for the Southern Hemisphere are not available. The mean monthly topographies of the isobaric surfaces over Antarctica published in two preliminary IGY Reports (Alvarez and Rastorguev [2]; Alt, Astapenko, and Ropar [1]) do not extend far enough toward the middle latitudes to give adequate measures; moreover, they cover only a part of the period which can now be considered. The South Pole station has been taken as representative of the inner part of the SCPV, in spite of the fact that in several months the center of the vortex cannot be found exactly over the Pole. This does not essentially affect the conclusions to be reached, as the mean pressure gradients (or gradients of height of isobaric surfaces) between 90° S. and the center of the vortex remain always small in comparison to the gradients between the inner polar zone and the middle latitudes.

2. RESULTS

Figure 1 shows the annual march of the height differences for 5 levels from 700 to 100 mb.; the monthly values of a period of 3 years, April 1957 to March 1960, have been used. Table 1 and figure 2 give corresponding values of the amplitude and phase of their first and second harmonic components, and the sum of the amplitudes of the higher harmonics. As the data for 100 mb. were not available for Marion Island, the analysis for the 200-mb. level has been carried out with and without that station,

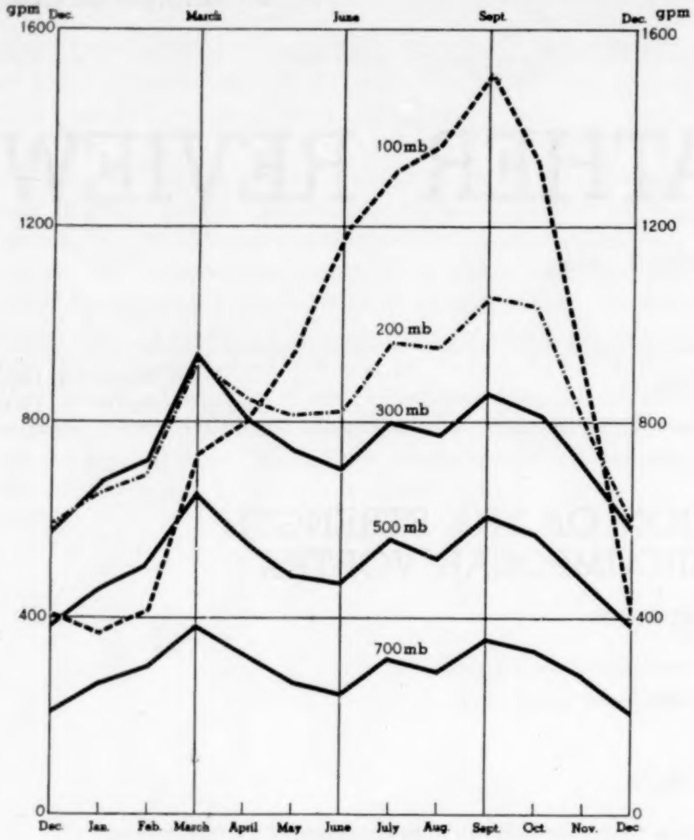

FIGURE 1.—The annual march of the height differences $\overline{H}$ (Invercargill plus Marion plus Port Stanley) $-H$(S. Pole) for 700, 500, 300 and 200 mb., and $\overline{H}$ (Invercargill plus Port Stanley) $-H$(S. Pole) for 100 mb. The location of the three subpolar stations is marked by solid circles in figure 4.

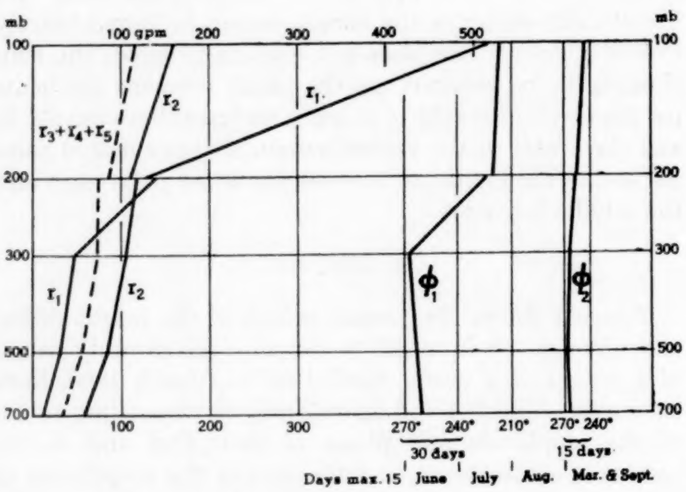

FIGURE 2.—Amplitudes and phases (days max.) of the first and second harmonic component of the annual march of $\overline{H}$ (Invercargill plus Marion plus Port Stanley) $-H$ (Pole), April 1957 to March 1960.

TABLE 1.—*Harmonic analysis of the annual march of the strength of the Southern Polar Vortex: Amplitude (r, in gpm.) and phase (ϕ) of the first and second harmonic, and sum of the residuals. April 1957 to March 1960.*

(a) $\overline{H}$ *(Invercargill, Marion, Port Stanley)* $-H$ *(Pole)*
(b) $\overline{H}$ *(Invercargill, Port Stanley)* $-H$ *(Pole)*
(c) $\overline{\Delta H}$ *(Invercargill, Marion, Port Stanley; 300–700 mb.)* $-\Delta H$ *(Pole; 300–700 mb.)*

Level (mb.)	Mean	r_1	ϕ_1	Day max.	r_2	ϕ_2	Days max.	$r_3+r_4+r_5$
(a) 700	297	10	260°	25.VI	58	263°	19.III+IX	33
500	523	30	263	22.VI	83	266	17	56
300	760	47	267	18.VI	105	262	20	73
200	841	139	223	2.VIII	119	257	22	75
(b) 200	815	128	219	6.VIII	110	256	22	87
100	937	518	216	9.VIII	160	244	28	117
(c) 300–700	463	39	267	18.VI	48	257	22	40

in order to show that there is no significant difference if Marion Island is included or not. The values in section (c) of table 1 refer to the meridional differences of the thickness of the 700- to 300-mb. layer which are equivalent to the mean meridional tropospheric (virtual) temperature gradient between 50° and 90° S.; for the layer considered, a variation in thickness of 25 gpm. corresponds to a variation of mean virtual temperature of 1° C.

The essential result is that the semiannual component is dominant in the troposphere, with the maxima appearing in the equinoctial months, (that is when the mean meridional temperature gradient is greatest), *and the simple annual component is dominant in the stratosphere.* (For a significance test of the semiannual periodicity, it is better to realize a harmonic analysis of the original series of 36 terms and to apply the method described by Brooks and Carruthers [3], (par. 18, 2), comparing the largest of the 18 possible harmonic components (that is, here the semiannual) with the "expectation"-value on the zero-hypothesis. This was done for the 300-mb. height differences ($\sigma=115$ gpm.) and for the 300–700-mb. thickness differences ($\sigma=57$ gpm.). It results that the amplitude of the semiannual harmonic component of both series exceeds the expectation calculated at the 1 percent level.) As a matter of fact, much more evidence as to the first part of the above italicized statement has been published in recent years (Schwerdtfeger and Prohaska [18, 19], Loewe [11]) and is implicit in other publications (Mintz and Munk [13], Hoffmeyr [7], Schumacher [17]), but for the present discussion it may be sufficient to refer to figures 1 and 2 and table 1. There may be no doubt at all about the second part of the above statement.

3. POSSIBLE EXPLANATION

The possible cause of this behavior of the SCPV can be tentatively assessed from the following considerations: *In the troposphere,* the meridional exchange ("Grossaustausch") between middle and polar latitudes is very strong; the small annual range of temperature, about the same at middle latitudes and polar zone of the Southern

Hemisphere, and especially the peculiar flat temperature curve of Antarctic stations during winter, is mainly due to the vigorous transport of subpolar air masses southward and the corresponding movement of polar air masses northward. The importance of this macro-turbulent process, which is mainly a consequence of the meridional temperature gradient, was recently stressed by Wexler [22, 23]. This meridional temperature gradient shows a characteristic annual march which, as will be discussed later, appears to be related to the seasonal variation of the radiative parts of the heat budget of different latitudinal belts, tending to produce larger mean temperature (or thickness) contrasts between middle and polar latitudes during the equinoctial months than around the solstices. There is a pronounced semiannual variation of the differences of daily totals of incoming radiation between middle (or subpolar) and polar latitudes, as is shown by means of the theoretical values (Milankovitch [12]) in figure 3. Of course, a semiannual variation in the heat budget of different latitudinal belts can be attributed to the effects of incoming solar radiation *only if* the other radiative terms determining the heat budget of the tropospheric air masses, particularly albedo and water vapor content, do *not* themselves show a pronounced *semi*-annual variation. This happens to be so, as far as can be deduced from the scarce observations up to now available; besides, it may be important to mention that in the annual march of the meridional differences of *surface* temperatures, the amplitude of the first harmonic exceeds by far that of the second harmonic.

In order to examine whether the meridional differences of those fractions of extraterrestrial radiation which are absorbed in the troposphere are of the right order of magnitude to be taken as a possible cause of the observed meridional temperature differences, the following assumptions are made: that the layer between 300 and 700 mb. absorbs about (a) 15 percent of the extraterrestrial radiation at 50° S., and 10 percent at 80° S., and (b) 20 percent and 15 percent, respectively (these are only estimates, but are in reasonable agreement with Fritz [4], Liljequist [10] and Hanson [6]). Table 2 gives the differences of the amounts of absorbed radiation in ly./month between latitudes 50° and 80° S.

The essential result is that the amplitude of the second harmonic of the annual march of the "differential heating" exceeds that of the first harmonic, and that its value

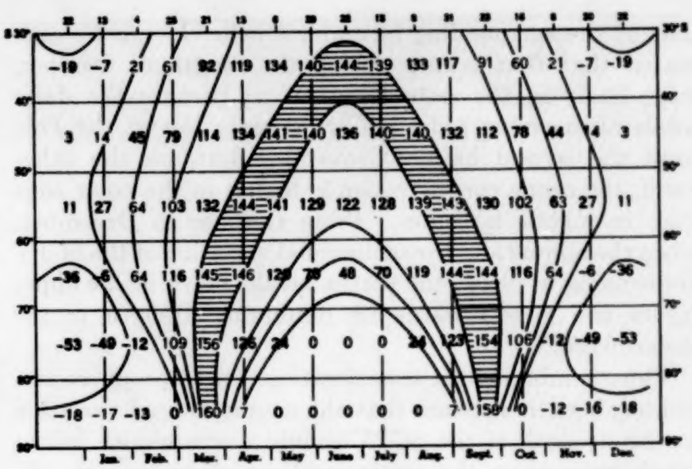

FIGURE 3.—Annual variation of 10° latitude differences of daily totals of incoming radiation between 30° and 90° S. The values are derived from table 1 of the work of Milankovitch [12], with $I=2$ ly./min.

(r_2) is several times greater than that which would be needed, in the hypothetical case of absence of macro-turbulent meridional exchange, to account for the observed value of r_2 in the annual march of the meridional thickness differences (table 1, section c). Therefore, it is strongly suggested that the semiannual variation of the meridional differences of absorbed radiation can bring about the seasonal change of the difference between the mean temperatures (or thicknesses) of middle and polar latitudes, the maxima occurring in the equinoctial months.

In the stratosphere, the conditions are different. The density of the air and the lapse rate being small (for more detailed reasoning see Rubin [15], Wexler [22, 23], and Palmer [14]) the compensating macro-turbulent meridional exchange of air, and therewith of heat, can not be sufficiently efficient. Even if the difference between incoming solar radiation at middle and polar latitudes is greater in March and September than in May through August, the dominating feature is that the cooling of the polar stratosphere continues through midwinter. Therefore, the SCPV in the stratosphere forms again when the incoming solar radiation at the highest latitudes diminishes noticeably and the differential heating begins to favor the middle latitudes, and remains until the springtime heating of the polar stratosphere becomes stronger than

TABLE 2.—*Meridional differences (50°–80° S.) of estimated values of radiation absorbed in the 300–700-mb. layer, ly./month. (a) and (b): Different absorption conditions assumed, as specified in the text.*

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
(a)	1510	1960	2190	1790	1110	780	940	1490	2010	2090	1560	1430 ly./mo.
(b)	1490	2250	2820	2360	1480	1060	1220	1980	2680	2570	1750	1290

Harmonic analysis:

(a) $r_1=320$ ly./mo.; $r_2=530$ ly./mo.; $\phi_1=79°$; $\phi_2=260° \approx$ max. at Mar. and Sept. 20
(b) $r_1=160$ ly./mo.; $r_2=810$ ly./mo.; $\phi_1=79°$; $\phi_2=258° \approx$ max. at Mar. and Sept. 21

that of the surrounding latitudinal belt. It can be estimated that that occurs during the month of October, more likely in the second half of it, because the daily totals of incoming radiation are slightly less at the Pole until the second half of November but, on the other hand, the ozone concentration is higher in the polar zone than in middle latitudes. From October to December, when the annual and the semiannual variation of the SCPV are running in phase, the vortex breaks down in the upper layers and goes towards its minimum strength in the troposphere.

Thus, combining the considerations for troposphere and stratosphere, it appears that the simple annual variation in the strength of the SCPV should increase with height much more than the semiannual variation, as the efficiency of meridional exchange diminishes with increasing height and the summertime heating, because of the effects of ozone, is restricted to the upper levels. That is essentially what the data in table 1 confirm. The relatively small increase with height of the second harmonic component in the stratosphere can be attributed to the lesser effects of the meridional differences in available energy on the difference between the heat budgets of middle and polar latitudes, and partially, also, to the asymmetry in time and increasing annual range of the yearly temperature curve of the polar stratosphere with height.

For completeness, the above qualitative statements should be supported by numerical estimates of the decisive terms. This is, of course, beyond the aim of the present note.

4. CONSEQUENCES

If the behavior of the SCPV is understood as the combined result mainly of radiation processes and macro-turbulent meridional exchange, some important consequences can be tentatively outlined:

(1) For the formation of the *semi*-annual variation of the SCPV, which is dominant in the troposphere and still quite noticeable in the lower stratosphere, the existence of the Antarctic continent is not an essential point (and, of course, neither is that of the other land masses of the Southern Hemisphere). Generally speaking, and referring only to the second harmonic of the annual march, the same should happen if the Antarctic did not exist. *Therefore, the semiannual variation in the strength of the SCPV may be considered as an essential feature of a planetary circulation.* As far as the author knows, this point was never mentioned in any work on the general atmospheric circulation, but it could have some importance for theoretical and perhaps also for experimental studies.*

(2) The slow buildup and fast breakdown of the SCPV, with the semiannual variation the dominant characteristic in the troposphere (that is, in the layer of the main part of the mass of the atmosphere), is nicely reflected in the mean annual variation of pressure at the surface. In 1955 and 1956, Schwerdtfeger and Prohaska [18, 19] published an analysis of the annual march of pressure for the world, trying to include for the first time the whole Southern Hemisphere. It was shown that there exists a very pronounced semiannual oscillation over the extratropical southern latitudes, with opposite phase values in polar (maxima at the solstices) and middle (maxima at the equinoxes) latitudes. This result, based on relatively short series of data south of 50° S., was supported by the data from an entirely independent study of Gordon [5], who considered the monthly change of mass of different latitudinal belts of the atmosphere between the *North* pole and 50° *S*. The corresponding values south of 50° S. have been computed by Schwerdtfeger ([21] table 2). The concept of a well marked semiannual pressure oscillation in polar regions is now also confirmed by the somewhat longer series of observations available at the end of the IGY. Schwerdtfeger and Prohaska [18, 19] suggested that the semiannual component in the yearly march of pressure over the extratropical part of the Southern Hemisphere is directly related to the corresponding variation in the strength of the circumpolar westerlies, and some evidence for this was brought forward by the authors and by Loewe [11]. It can now be said more explicitly that the annual march of surface pressure over polar and middle southern latitudes should be considered the consequence (the "demonstration at the surface") of the annual march of the strength of the SCPV. It does not seem necessary to reproduce here the already published results of the harmonic analysis of the Southern Hemisphere pressure field. However, it is interesting to point to the mean change of pressure at the surface, related to the "breakdown" of the SCPV (from October to December, fig. 4).

(3) The semiannual variation of the mass of the polar atmosphere is of such an order of magnitude (the amplitude of the second harmonic amounts to about 3 per mille of the mass south of 60° S., the maxima occurring at the solstices) that its effect on the angular velocity of the earth, i.e., the length of day, must be noticeable. It appears that the calculations of Mintz and Munk [13] can thus be refined.*

(4) Finally, it should be remarked that the old notion of classic climatology, not objected to until 1955 (Schwerdtfeger and Prohaska [18]), that the semiannual oscillation of surface pressure may have its main origin in the equatorial zone, cannot be maintained in the light of the results from the Southern Hemisphere.

Additional remark, referring to the occurrence of a semiannual variation in the strength of the tropospheric circumpolar westerlies at high *northern* latitudes: In the case of the Northern Hemisphere, it can not be expected that the zones of equal heat budget be latitudinal belts and that the meridional temperature gradients at higher

*Scherhag's [16], contention, that "all essential features of a planetary circulation can be seen from the mean annual topography of the 1000 mb. surface [sic!] of the southern hemisphere," can hardly be accepted.

*This problem will be considered in a separate paper.

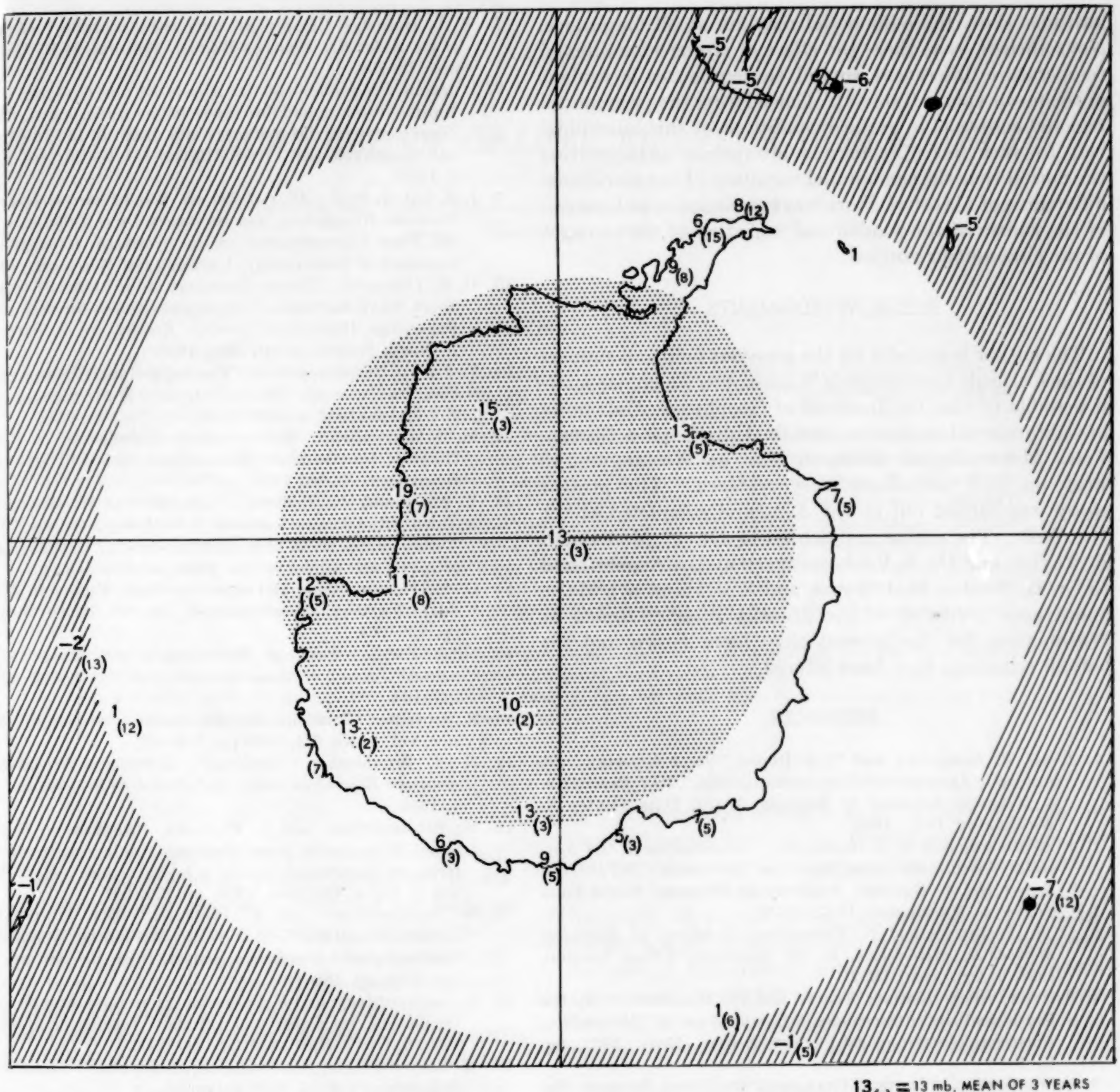

FIGURE 4.—Mean pressure change (mb.) from October to December, Southern Hemisphere south of 40° S. Hatching shows zone of negative values; stippling, zone of values>10 mb. For all stations with a record less than 20 years, the number of years used is put in parenthesis.

TABLE 3.—*Latidudinal means: (a)u-component of the geostrophic wind at 300 mb., average of 65°, 70°, and 75° N., 1950–57, computed from Lahey, Bryson, et al. [9]; (b) 500–1000-mb. thickness differences, 60°–80° N., (20 gpm. ≈ 1° C.), 1900–39, computed from Jacobs [8].*

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	
(a)	6.8	6.6	8.0	7.6	6.2	6.4	7.0	7.6	8.8	9.0	7.9	7.1/	m./sec.
(b)	124	139	196	200	168	143	146	155	169	184	150	135	gpm.

Harmonic analysis

(a) r_1=0.7 m./sec., max. at October 15; r_2=0.9 m./sec., max. at Mar. and Sept. 28.
(b) r_1=11 gpm., max. at May 18; r_2=30 gpm., max. at Apr. and Oct. 6.

latitudes show the equinoctial maxima at all longitudes. Nevertheless, even there the effect of stronger meridional temperature differences around the equinoxes is evident in the mean values (table 3). Considering the pronounced regional contrasts in surface conditions of this latitudinal belt, the fact that $r_2 > r_1$ may be interpreted as supporting the notion that the semiannual variation of the meridional differences of absorbed short-wave radiation is at least one of the causes of the semiannual variation of the strength of the circumpolar vortices.

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ON THE PRACTICAL USE OF GRAPHICAL PREDICTION METHODS[1]

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ABSTRACT

Useful forecasts may be obtained by graphical integrations of the dynamical prediction equations for a barotropic and a two-level baroclinic atmosphere. Such forecasts may be prepared without the aid of special equipment and are therefore particularly valuable as a means of training forecasters in physical prognosis.

The present paper reviews the physical principles, modeling assumptions, and methods of solution used in graphical prediction and introduces a method of obtaining surface forecasts which is considerably faster and simpler than previous methods. The predicted surface pressure is shown to be the sum of two components: (1) the pressure advected to the spot by one-half the 500-mb. wind and (2) a pressure change reflected down from aloft (actually one-half the 500-mb. height change expressed in equivalent pressure units at 1000 mb.). The movement of surface pressure systems is thus seen to be largely dependent on upper-level steering, while the deepening is found to be related to the vorticity advection at high levels, since this mainly determines the 500-mb. height changes.

Twenty sample surface forecasts prepared by the graphical method during July 1959 are presented and compared with the forecasts for the same dates issued by the National Weather Analysis Center. Little difference in accuracy is apparent.

Typical shortcomings and failures of the graphical prognoses are discussed. It is believed that the most serious errors are due to the use of only the initial 500-mb.charts in advecting the pressure systems. If the 500-mb. forecasts had been available earlier, it appears that a significant increase in accuracy could have been achieved by using both initial and forecast 500-mb. contours in performing the advections.

1. INTRODUCTION

The purpose of this paper is first to present a fast and simple method for preparing surface prognostic charts based on the graphical methods introduced by Estoque [1] and Reed [2], second, to show by examples the generally useful caliber of the forecasts obtained by the method, and third, to discuss some of the characteristic failures of the forecasts and possible ways of overcoming them. Graphical prediction, as referred to here, is a form of numerical prediction in which the dynamical equations are integrated by graphical operations rather than by machine computation. The technique of graphical integration was originated by Fjørtoft [3].

From the results presented in section 6 it will appear that the graphical method has possible useful application in the field today. However, it is felt that the principal advantage of the method lies not in its practical applications but rather in the physical insights it offers the forecaster regarding the movement and development of pressure systems and in the better appreciation it gives him of the dynamical approach to forecasting. Empirical rules, such as the steering of surface systems by the upper-level flow and the displacement of 500-mb. features by the space-mean flow, are shown to have a sound physical basis, and dynamical formulas or techniques of limited or overlapping scope, such as the Rossby wave formula and constant absolute vorticity trajectories, are brought within a single, broad framework.

The value of a unified, as opposed to a piecemeal, approach to the forecast problem is particularly apparent in the case of the student forecaster. The experienced forecaster may profitably include a variety of techniques in his "bag of tricks," though even in his case there is something to be said in favor of a unified outlook.

2. THE EQUATIONS AND THEIR LIMITATIONS

Before proceeding to the practical forecast procedure, it is desirable to present the basic equations and to recognize their limitations. For the 500-mb. forecast, the prediction equation is [3]

$$\frac{d}{dt}(\overline{Z}_5-Z_5+G)=0, \tag{1}$$

where Z_5 is the geopotential height of the 500-mb. surface, $\overline{Z}_5$ is the space-mean 500-mb. height, usually measured at the corners of a square grid of 600–1000 km. mesh size, and G is a measure of the Coriolis parameter. The equation is essentially a statement of the conservation of absolute vorticity, and therefore assumes that a level of nondivergence exists in the atmosphere (near 500 mb.).

[1] The research reported on here was supported in part by the Geophysical Research Directorate of the Air Force Cambridge Research Center under Contract AF 19(604)-3063.

Geostrophic motion is also assumed. Since absolute vorticity is conserved, it is apparent that this equation is unable to predict development or intensification.

The additional equation needed to extend the prognosis to 1000 mb. is [2]

$$\frac{d}{dt}(\overline{Z}_0-Z_0+G+kZ_T)=0, \tag{2}$$

where the subscript zero refers to the 1000-mb. level, k is a parameter (assumed constant) which depends on the mesh size, static stability, and the Coriolis parameter, and Z_T is the 1000–500-mb. thickness. Equation (2) is derived from the vorticity and thermodynamic energy equations under the assumptions of geostrophic, adiabatic, and frictionless motion. Also assumed are a functional relationship of the vertical velocity with height, with zero vertical velocity at the surface (level ground), and a straightline wind hodograph between 1000 mb. and 500 mb. The equation may be regarded as a special form of the potential vorticity theorem.

3. METHODS OF OBTAINING EXACT SOLUTIONS

The local change of $\overline{Z}_5-Z_5+G$ in (1) is obtained graphically by advecting this quantity the desired time interval in the geostrophic flow corresponding to the $(\overline{Z}_5+G)$-field and graphically subtracting the later field from the initial. Thus,

$$\Delta(\overline{Z}_5-Z_5+G)=-A_5, \tag{3}$$

where A_5 is the result of the subtraction. Therefore,

$$\Delta\overline{Z}_5-\Delta Z_5+A_5=0. \tag{4}$$

This equation can be solved either by means of a series expansion (Petterssen [4]) or by the relaxation method. The height change is then added to the initial height to obtain the predicted height.

In a similar manner the quantity $(\overline{Z}_0-Z_0+G+kZ_T)$ in equation (2) is advected with the geostrophic wind corresponding to the $(\overline{Z}_0+G+kZ_T)$-field to give an advective change, A_0. Thus

$$\Delta(\overline{Z}_0-Z_0+G+kZ_T)=-A_0, \tag{5}$$

or, upon substitution of Z_5-Z_0 for Z_T,

$$\Delta\overline{Z}_0-(1+k)\Delta Z_0+k\Delta Z_5+A_0=0. \tag{6}$$

Since ΔZ_5 is known from the results of (4), equation (6) can be solved for ΔZ_0 by either of the two methods mentioned above.

4. A METHOD OF OBTAINING SHORT, APPROXIMATE SOLUTIONS

To carry through all the operations implicit in the solution of equation (6) is a tedious and time-consuming job. However, on the basis of several years of experience with the method, both in research studies and classroom exercises, a number of short cuts have been developed which greatly shorten the procedure and which do not appear to have adverse effects on the accuracy of the forecasts.

When use is made of a 6° lat. mesh size, as originally suggested by Fjørtoft, variations of the quantity G in equation (1) are found to be small compared with variations of $\overline{Z}_5-Z_5$. Thus (1) may be simplified to

$$\frac{d}{dt}(\overline{Z}_5-Z_5)=0, \tag{7}$$

and the $\overline{Z}_5$ field alone determines the advecting wind. A further simplification results from measuring advective changes only at fixed grid points rather than continuously over the chart. With the help of a displacement ruler, the upstream value of $\overline{Z}_5-Z_5$ is advected to the point and is subtracted from the current value at the point to give A_5. In performing the advection four-fifths, rather than the total, geostrophic wind is used. This factor has been determined empirically and presumably compensates for the neglect of G and for a deviation, in the mean, of the level of nondivergence from the assumed level of 500 mb. Next it is assumed that $\Delta\overline{Z}_5$ is negligible aside of ΔZ_5 so that equation (4) may be written

$$\Delta Z_5=A_5. \tag{8}$$

Since the advection at a single grid point may be performed very rapidly and since the advections may be divided among a number of persons, a considerable saving of time is realized by making measurements at individual points. To take advantage of a team effort a master chart with grid points superimposed and duplicating facilities are required.

Once the 500-mb. height changes are computed, isopleths are drawn for use in the next step.

Next equation (2) is simplified by noting that the variations in $\overline{Z}_0$ and G are generally small compared with those in Z_0 and kZ_T. Thus (2) reduces to

$$\frac{d}{dt}(KZ_5-Z_0)=0, \tag{9}$$

where $K=k/(1+k)$ and Z_5-Z_0 has been substituted for Z_T. It can be shown that the advecting wind in (9) is now the geostrophic wind corresponding to KZ_5 (Estoque [1]). Consequently

$$\begin{aligned}\frac{\partial}{\partial t}(KZ_5-Z_0)&=-K\mathbf{V}_{g5}\cdot\nabla(KZ_5-Z_0)\\&=K\mathbf{V}_{g5}\cdot\nabla Z_0.\end{aligned} \tag{10}$$

Integration of (10) over the forecast interval, assuming no time variation of $\mathbf{V}_{g5}$, gives

$$K\Delta Z_5-\Delta Z_0=Z_{0t}-Z_{0u} \tag{11}$$

where Z_{0i} represents the initial 1000-mb. height at a point and Z_{0u} the value upstream which is advected to the point during the forecast interval.

Denoting now the predicted 1000-mb. height by Z_{0p} and noting that

$$Z_{0p}=Z_{0i}+\Delta_0, \tag{12}$$

we obtain from substitution of (11)

$$Z_{0p}=Z_{0i}+(K\Delta Z_5+Z_{0u}-Z_{0i})=Z_{0u}+K\Delta Z_5. \tag{13}$$

Since a typical value for K at middle latitudes is 1/2 and since this is a convenient number which gives good results in practice, we write as the final prediction formula,

$$Z_{0p}=Z_{0u}+\frac{1}{2}\Delta Z_5. \tag{14}$$

Equation (14) states the interesting result that the 1000-mb. height (or surface pressure) may be predicted by displacing (steering) the surface pressure pattern with a fraction (one-half) of the 500-mb. wind and adding a fraction (one-half) of the 500-mb. height change, a result which has long been known, at least in part, from empiricism. Thus both upper-level steering and reflection of height changes from aloft are shown to be important in the behavior of surface pressure systems. The upper-level change is particularly important in the problem of development and attests to the importance of the advection of vorticity at high levels in the deepening of surface Lows, as discussed by Petterssen [5] and others.

The final steps in obtaining the forecast consist of advecting 1000-mb. heights to the grid points (using one-half the geostrophic velocity at 500 mb.), analyzing the new pressure field, and then graphically adding the field of 500-mb. height change. The half factor is taken account of by relabeling the height changes with one-half values before addition.

The use of grid points, as before, has the advantage of allowing the advections to be divided among several workers. This advantage in speed would be offset by a loss in accuracy if an advective change were determined in this stage, rather than an advected pressure. Unless an exceedingly fine grid is used, important features of the pressure field are lost when changes at grid points are analyzed and added to the initial field. However, by advecting and analyzing pressures, the forecaster can be certain that these features are maintained. He visually affirms that the preliminary pressure analysis truly represents a displaced version of the original chart. The addition of the upper-level changes usually results in only minor modifications of this preliminary pressure field, though these modifications are important in that they determine the deepening and filling of the surface pressure systems, as mentioned before.

5. SUMMARY OF THE SHORT PROCEDURE

It is assumed that the field of 500-mb. height change is available either from the graphical method or preferably from the more exact solution of the barotropic vorticity equation transmitted by the National Weather Analysis Center.

Step 1. Superimpose surface and 500-mb. charts on a map containing grid points. Surface isobars should be drawn at 4-mb. intervals (approximately equivalent to a 100-ft. contour interval), 500-mb. contours at 200-ft. intervals, and grid points at about a 4° lat. separation. Prepare duplicate copies.

Step 2. By application of a geostrophic displacement scale to the 500-mb. contours, determine the surface pressure at the appropriate point *upstream* from the grid point and record this pressure at the grid point. If duplicate charts have been prepared, this work may be shared by a team of workers. Because of the one-half factor, it is important to note that the 200-ft. contour interval is treated as only a 100-ft. interval in applying the geostrophic wind scale. The measurements should be made along contour channels, using a flexible ruler, and allowance should be made for variations of speed along the channels.

Step 3. Analyze the preliminary prognostic pressure field making sure that the analysis represents a displaced version of the initial pressure distribution. Take special care with positions of high and low centers and frontal troughs.

Step 4. Graphically add the 500-mb. height changes to the preliminary pressure chart to give the final prognostic chart. If surface isobars are at 4-mb. intervals, height changes should be at 200-ft. intervals (because of the one-half factor).

Experience has suggested a few modifications of the prognostic chart which generally lead to improved forecasts. These will be discussed in section 7.

6. SOME SAMPLE FORECASTS

In order to demonstrate the quality of the forecasts obtained by the foregoing method the results of 20 predictions of surface pressure made during July 1959 are presented in figure 1. The prognostic charts were prepared by students, under the guidance of the instructors, in a special course for Air Force officers held during the summer session at University of California at Los Angeles. Also shown in the figure are the corresponding prognostic charts received by facsimile from the National Weather Analysis Center and the verification charts. Missing days are due to weekends and variations in the laboratory routine, not to a selection of cases.

In comparing the prognostic charts based on the graphical method with the subjective prognoses from the Analysis Center, it is important to note that the latter are for a somewhat longer time period (30 hours) and therefore may appear to be of poorer quality than the graphical prognoses even though they possess greater skill. With this proviso in mind, it would appear from examination of

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FIGURE 1.—Interrupted series of surface charts for period July 1 to August 1, 1959. Left, observed chart; center, 24-hr. prognostic chart, Reed method; right, 30-hr. prognostic chart, National Weather Analysis Center.

FIGURE 1.—Continued.

FIGURE 1.—Continued.

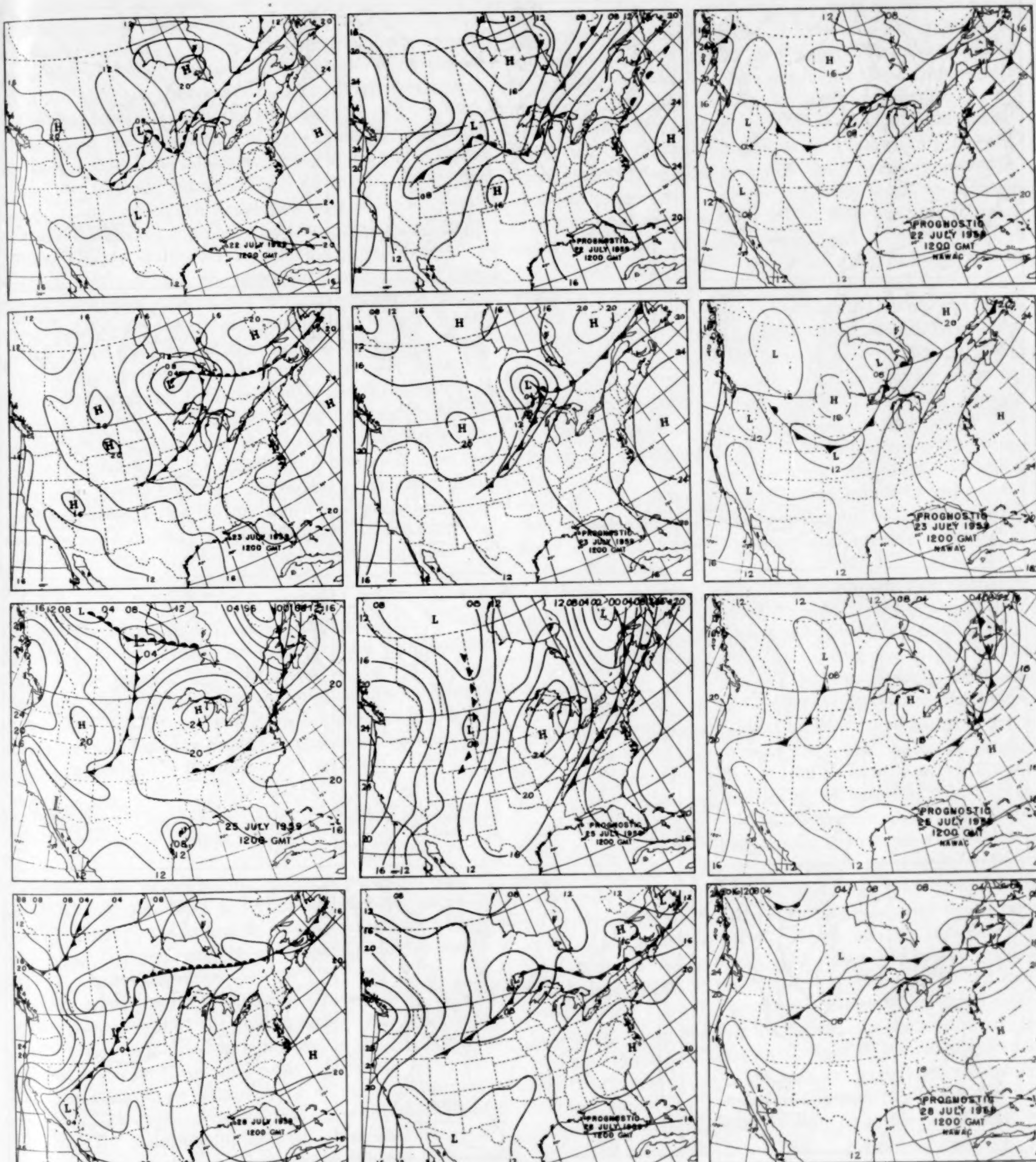

FIGURE 1.—Continued.

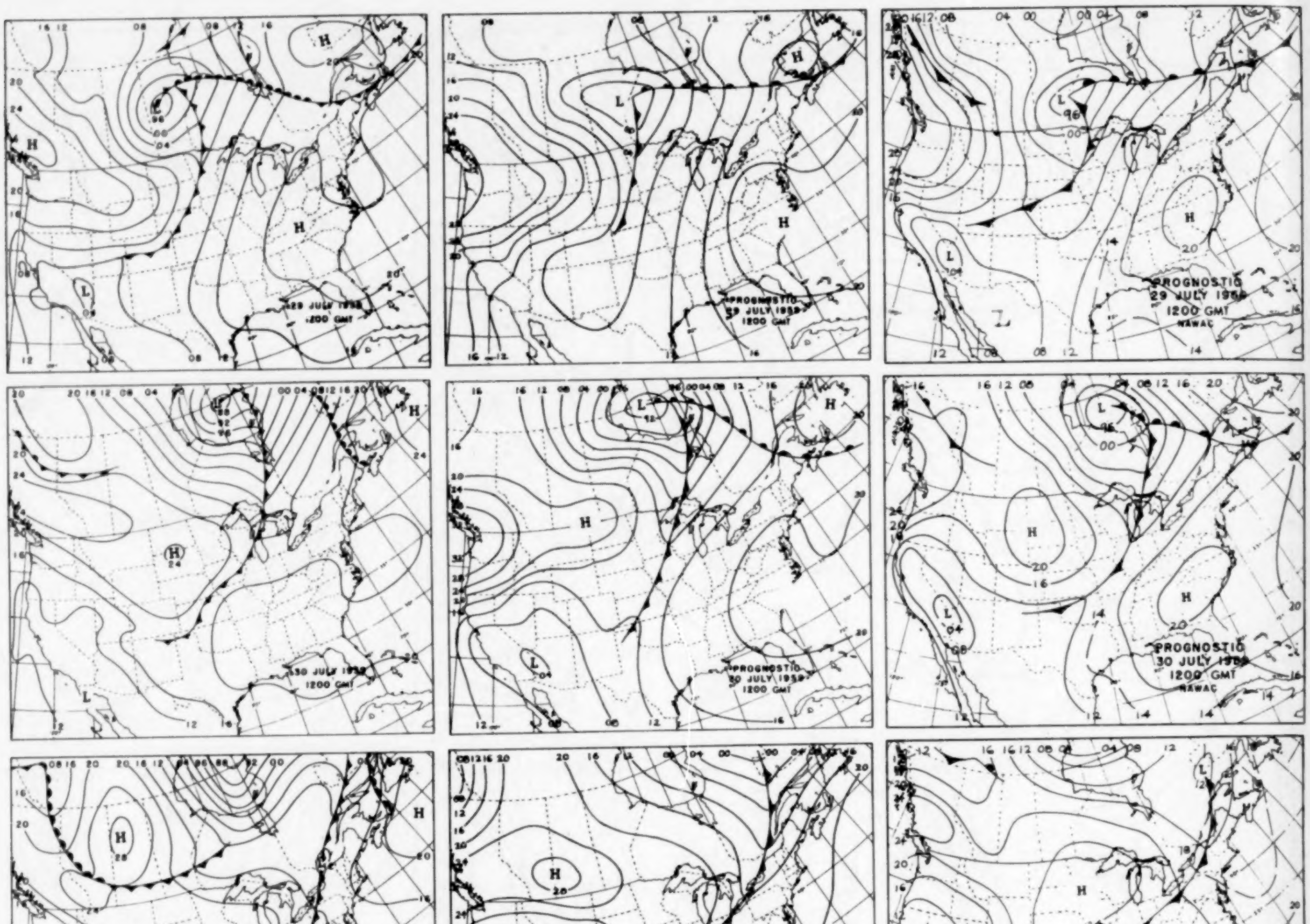

FIGURE 1.—Continued.

the charts that there is little difference in the accuracy of the two types of forecasts. On most days the prognoses bear a fairly close resemblance to each other and also to the verification chart. Where errors in the displacements of cold and occluded fronts or low centers occur, almost always the subjective forecasts show an overdisplacement and the graphical forecasts the contrary.

Concerning the forecasting of development, it appears that the graphical method is superior, though the difference in the forecast interval may be important in this respect. The Low which developed near Lake Michigan on July 1 was missed completly by the subjective method, but was clearly indicated in the graphical prognosis. This Low resulted from the downward reflection of relatively large height falls at 500 mb., and its development was even more apparent at intermediate stages in the preparation of the forecast than on the prognostic chart.

The filling of the original low center near southern Hudson Bay and the formation of a new Low north of Minnesota on July 4 was hinted at on the graphical prognosis but not on the subjective. On July 8, the subjective forecast, contrary to the graphical, showed a new low center over North Dakota. From the verification chart it is apparent that this feature failed to materialize. On the other hand on July 21, the subjective forecaster did a better job of predicting the wave development over Montana, though its presence was evident on the graphical prognosis.

In a few cases bad features of the forecasts were traced to student errors—for example, the poor position of the warm front in New England on July 2 and the overdisplacement of the low center in southern Canada on July 28. Because of emphasis on large-scale features no attempt was made to predict the hurricane of July 7–10 in the eastern United States.

7. FURTHER COMMENTS AND SUGGESTIONS FOR IMPROVEMENT

On the basis of rather extensive experience with the graphical method, both in synoptic laboratories and in research studies, the following observations may be made concerning the performance of the method and possible ways of improvement.

1. The performance is better in summer than in winter probably as a result of the greater persistence and regularity of long-wave features in summer and the less rapid and extreme development of short-wave systems.

2. It is possible to allow for the effect of mountains in generating lee troughs and crest ridges by procedures suggested by Estoque [6] and Haltiner and Hesse [7]. In the short method described here the effect is equivalent to adding to the 500-mb. steering field an additional geostrophic wind field, determined by a fraction of the topographical contours. Thus surface pressure systems tend to acquire an additional southward component of movement on the east sides of mountain ranges and an opposite movement on the west.

No attempt was made to take orographic influences into account in the present series of forecasts, but qualitative comparison of the actual and prognostic charts leaves little doubt that the forecasts would have been consistently improved by incorporating the effect of orography.

3. The development of new waves is usually too weakly predicted. A typical example is the case of July 1, 1959. Since cyclogenesis is characteristically overemphasized in machine integrations using short time steps, it appears that this feature is connected with the long time interval employed in the graphical integration.

4. Along most of their extents cold and occluded fronts are displaced with one-half the 500-mb. wind, as required by the model. In the vicinity of cols, however, where the upper-level flow often parallels the surface front, the movement appears to be governed more by frictional outflow at low levels. In such cases the cold air advances generally at a speed of about 5 knots despite the absence of a geostrophic component normal to the front. This empirically derived fact was used in preparing the prognostic charts and was the only empirical correction applied. The relationship of warm fronts to upper-level flow is more erratic, probably as a result of the tendency of their lower portions to flatten and become retarded in certain situations.

5. The most serious shortcoming of the graphical method is the use of a single large time step in the integration. In other words, as applied here, the method makes no allowance for the change in steering current during the forecast period. It is believed that the underdisplacement of fronts in this series was almost entirely due to this cause.

Because of the usual location of surface Lows under a more or less straight current aloft, the change in upper-level flow generally does not lead to serious errors in their displacements during periods of 24 hours or less. However, surface Highs oftentimes are situated just to the rear of upper-level troughs. In such cases the one-step integration carries the High around the trough, while in retrospect the movement of the trough may be sufficient to prevent the High from advancing beyond the trough line. The positions of the Highs on the forecasts for July 3 and 9 to the north of the observed positions may be accounted for by this type of error.

Since the 500-mb. prognostic chart is prepared independently, it is possible to correct the advection of the surface pressure systems in the light of the changes in the flow pattern aloft. As yet no tests have been conducted making use of the prognostic 500-mb. chart, but the impression is that such use would almost always lead to improved forecasts.

In view of the success of the 500-mb. forecast issued by the Joint Numerical Weather Prediction Unit, it would be of interest to use this in conjunction with the current 500-mb. chart in displacing Highs, Lows, and fronts, and

other significant features of the surface chart. The numerically predicted 500-mb. height changes would then be used to modify the preliminary estimate obtained from displacing the surface features. Experience with the graphical method would lead one to believe that highly useful forecasts may be obtained in this way.

It would also be desirable to arrive by statistical means at a better estimate of the coefficient for displacing surface pressure systems and reflecting down the 500-mb. height changes. The value used here (0.5) has been selected partly for convenience and does not necessarily represent the best value.

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AN EXPERIMENT IN THE USE OF "PERFECT" PROGNOSTIC CHARTS

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ABSTRACT

An experiment was conducted to determine how much if any, the 2-day forecasts for Utah, as issued by the forecast staff at Salt Lake City, would be improved if "perfect" prognostic charts were available for sea level, 700 mb., and 500 mb., for periods up to 48 hours. Results are discussed using the paired t test for differences between forecasts made from "perfect" prognostic charts and control forecasts, skill scores from precipitation contingency tables, and a non-parametric "Rank Method" comparison.

1. INTRODUCTION

There has been considerable discussion among forecasters from time to time concerning just how much weather forecasts would be improved if "perfect" prognostic charts of sea level pressure and frontal positions, as well as upper-air contours, were available. In the light of these discussions, it was decided to conduct an experiment among the forecasters at Salt Lake City to determine, insofar as possible, how much the 2-day Utah State forecasts would be improved if the prognostic charts referred to above, which are received via facsimile from the National Meteorological Center (NMC) in Suitland, Md. were "perfect."

2. PROCEDURE

This experiment was conducted in somewhat the same fashion as an experiment described by Panofsky and Brier [1] in their chapter on "Sampling Theory." In that experiment, forecasts were made first with incomplete observational data. After this initial forecast was completed, additional data were furnished to the forecaster and a revised forecast was prepared. Results were then analyzed to determine whether the additional data improved the forecasts, and if so, by how much. In the Salt Lake City experiment, forecasts were first made in the conventional manner, with most of the observational and chart material ordinarily available to the forecaster. Then perfect prognostic charts were supplied and a revised forecast made.

A month sufficiently removed from the time of the experiment (early 1959) had to be selected in order that forecasters would not recall the sequence of weather events. Also an active month with considerable precipitation and variation in temperature was needed, so as to make the test meaningful, yet with no outstanding or unusual weather events, for these might be retained in an attentive forecaster's memory. April 1953 met the requirements satisfactorily, and so was chosen for the experiment.

Forecasts were made from the 1730 MST surface map, for the three periods: tomorrow, tomorrow night, and the second day. Data available to the forecasters were the surface map, 700-mb. and 500-mb. charts, plotted raobs, and hourly sequence reports. Forecasts were made for five stations in Utah (Salt Lake City, Delta, Cedar City, Roosevelt, and Blanding) and included the 24-hour change in maximum or minimum temperature and precipitation for the three 12-hour periods. Forecasts were also prepared for tomorrow's maximum, tomorrow night's minimum, and the second day's maximum temperature for Salt Lake City only. Verification was tabulated on the present U.S. Weather Bureau "State forecast forms," using the rules for same, with a "trace" of precipitation considered as no precipitation. A temperature change of $\pm 9°$ F. was required to "break" a no-change forecast, while a change of 1° F. in the right direction verified a warmer or colder forecast. Since five stations were involved, 20 percent was deducted for each incorrect forecast. Thus scores for each period were either 0, 20, 40, 60, 80, or 100 percent for both precipitation and temperature change forecasts.

After the initial (control) forecasts were made, the perfect prognostic charts were made available to the forecaster, and he was instructed to make a revised forecast. The prognostic charts given to the forecaster were selected so as to represent fairly closely the pressure and contour prognostic material available by facsimile from NMC. At the time of the experiment, the latter provided sea level, 700-, and 500-mb. prognostic charts for approximately 12, 24, 36, and 48 hours in advance. Frontal intensities were labeled on the sea level prognostic charts, as is customarily done by NMC.

Five of the staff forecasters took part in the experiment, each making forecasts on from five to eight days, for the three periods mentioned above. Since forecasts were

made each day in April, there were 30 forecasts for comparison between perfect prognostic and control forecasts. No comparison was made between forecasters, as Panofsky and Brier did. Also, no forecaster made forecasts on consecutive days, as after completing his initial 48-hour forecast, the forecaster was given prognostic material for two days ahead. However, this restriction made the individual forecasts more independent, since most of the day-to-day serial correlation between overlapping forecasts was eliminated. It is well known that when forecasting under doubtful conditions a forecaster frequently tends to repeat his forecast for the overlapping period, applying a sort of "double or nothing" philosophy.

Since it was desired that full use be made of the prognostic charts, including the implicit temperature forecasting features [2], 1000-mb. charts were made from the sea level prognostic charts, and these were used to construct perfect 1000–700- and 1000–500-mb. thickness prognostic charts. Departures from normal thickness were also supplied to the forecaster. Each forecaster was aware of the relationship between mean virtual temperature of the layer and thickness; i.e., a thickness change of 200 ft. represents a 5.5° F. mean virtual change in the 1000–500-mb. layer, and an 11° F. change in the 1000–700-mb. layer. Using this information is, of course, merely extracting fully the information implicitly available from prognostic charts, perfect or imperfect [3, 4].

3. RESULTS

Average scores for perfect prognostic and control forecasts are shown in the top part of table 1. Results are given for precipitation and temperature forecasts for the three periods, both separately and combined. These periods are respectively 12–24, 24–36, and 36–48 hours in advance, and are labeled 1, 2, and 3 in the table. It can be seen (left and center columns) that the perfect prognostic scores (percent correct) for the State forecasts are better for all but the first-period precipitation, and are especially better for third-period precipitation. For precipitation forecasts, the longer the forecast interval, the more the perfect prognostics help, as perfect prognostic scores essentially hold steady with increasing time, while control forecasts show a rapid decrease in accuracy.

The Weather Bureau State forecast temperature change verification scheme used here is relatively insensitive because there is a large overlapping where two different forecasts may be correct. It was felt that a forecast of actual temperature might give a more sensitive verification, so forecasters were also requested to predict actual temperatures for tomorrow's maximum, tomorrow night's minimum, and the second day's maximum at Salt Lake City. Average errors in degrees F. are shown in the right-hand columns of table 1. Since lower average errors represent better forecasts, differences are considered positive when the perfect prognostic forecasts are better.

It may be noted that both types of temperature forecasts are more improved for maxima (periods 1 and 3) than for minima (period 2) by use of the perfect prognostic charts. This is probably because maximum temperatures are more representative of the air mass than minimum temperatures in the area and season under consideration, and thus are more readily forecast from the perfect thickness prognostic charts. The correlation between maximum temperature and 1,000–700-mb. thickness (interpolated values) for April 1953 for four stations in Utah was 0.86, while between minimum temperatures and thickness it was only 0.66.

A number of statistical methods can be employed to test the significance of the results. First the t test, using the method of paired comparisons [5], was used to test whether perfect prognostic forecast scores were significantly different from control forecast scores. Those days for which the two forecast scores were identical were not included since these give no information about differences in forecasting skill. Results of this test are shown in the lower portion of table 1. It may be seen from the last row, labeled Probability, that the perfect prognostic third-period precipitation forecasts are better than the control forecasts at the 3 percent level of significance. No other precipitation scores are significantly different. For temperature change (State forecast) no individual period differences are statistically significant, but com-

TABLE 1.—*Comparative scores and results of* t *test*

	Precipitation (State forecasts)				Temperature change (State forecasts)				Salt Lake City actual temperature forecasts			
Period	1	2	3	Combined	1	2	3	Combined	1	2	3	Combined
N	30	30	30	30	30	30	30	30	30	30	30	30
Aver. score {P. Progs	82.0	82.7	83.3	82.6	86.7	81.3	82.0	83.3	3.9	3.6	5.6	4.3
Aver. score {Control	86.0	79.3	72.0	79.0	78.7	78.0	74.3	77.0	5.3	4.6	7.3	5.7
Difference	−4.0	3.4	11.3	3.6	8.0	3.3	7.7	6.3	1.4	1.0	1.7	1.4
Results of t tests												
No. pairs	8	12	12	13	12	12	18	19	18	18	23	27
Mean diff.	−15.0	8.3	31.7	9.4	20.0	8.3	12.8	10.7	2.2	1.7	2.2	1.5
Std. error	15.9	9.1	11.4	4.9	13.5	11.4	7.9	4.1	0.92	0.80	0.98	0.48
t	−0.94	0.92	2.78	1.93	1.48	0.73	1.61	2.61	2.49	2.15	2.27	3.14
Probability	0.38	0.38	0.03	0.11	0.17	0.48	0.13	0.02	0.02	0.05	0.03	<.01

TABLE 2.—*Precipitation contingency tables*

		Period 1			Period 2			Period 3			All periods		
		Forecast			Forecast			Forecast			Forecast		
		R	NR	T	R	NR	T	R	NR	T	R	NR	T
Perfect prognostic forecasts													
Observed	R	10	9	19	7	14	21	10	8	18	27	31	58
	NR	18	113	131	12	117	129	17	115	132	47	345	392
	T	28	122	150	19	131	150	27	123	150	74	376	450
		Hits: 82 percent Skill score: 0.32			Hits: 83 percent Skill score: 0.25			Hits: 83 percent Skill score: 0.35			Hits: 83 percent Skill score: 0.31		
Control forecasts													
Observed	R	12	7	19	3	18	21	2	15	17	17	40	57
	NR	14	117	131	13	116	129	26	107	133	53	340	393
	T	26	124	150	16	134	150	28	122	150	70	380	450
		Hits: 86 percent Skill score: 0.45			Hits: 79 percent Skill score: 0.05			Hits: 73 percent Skill score: 0			Hits: 79 percent Skill score: 0.15		

bined perfect prognostic forecasts are significantly better at the 2 percent level. For Salt Lake City actual temperature forecasts in degrees F., the perfect prognostic forecasts are significantly better for all three periods, and the significance exceeds the 1 percent level for the combined forecasts.

Next, contingency tables were prepared for the precipitation forecasts for the three periods, both individually and combined, as shown in table 2. Chance skill scores and percent correct are also given. Since forecasts were made for five stations for each period each day, there are 150 individual rain or no-rain forecasts for each period for the entire month. Perfect prognostic forecasts show a lower skill score for the first period, but notably higher skill for the second and third periods.

A third comparison was made using the "Rank Method" as described by Panofsky and Brier [1]. In this method, no assumptions are made regarding the normality of frequency distributions. Forecast score differences are arranged in rank order (least difference, regardless of sign, is number 1, etc., after eliminating ties). The proper signs are then given to the ranks, and the rank differences for the fewest cases of the same sign are totalled. The smaller this number, the more significant the difference between the two forecasts. Table 3 shows the results of this comparison. It may be seen that the perfect prognostic forecasts are significantly better at the 5 percent level for third-period precipitation and temperature change, and for combined temperature change forecasts. For Salt Lake City actual temperatures, the perfect prognostic forecasts are significantly better at the 5 percent level for all three periods, and at the 1 percent level for combined forecasts. Control precipitation forecasts are better than perfect prognostic forecasts for first-period precipitation, but not significantly so. This agrees with the results shown in tables 1 and 2.

4. INTERPRETATIONS AND CONCLUSIONS

Significant improvement, based on results as shown by the *t* test, is noted in the perfect prognostic forecasts for all periods for actual maximum and minimum temperature forecasts, for combined temperature change forecasts, and for third-period precipitation forecasts. All other differences are not significant at the 5 percent level, and for first-period precipitation, control forecasts were actually better than perfect prognostic forecasts. Also, perfect prognostic minimum temperature change forecasts showed

TABLE 3.—*Results of Rank Method comparison*

Period	Precipitation (State forecasts)				Temperature change (State forecasts)				Salt Lake City actual temperature forecasts			
	1	2	3	Combined	1	2	3	Combined	1	2	3	Combined
No. pairs	8	12	12	13	12	12	18	19	18	18	23	27
No. times perfect prog. better	2	7	9	9	7	7	12	13	12	12	16	18
No. times control better	6	5	3	4	5	5	6	6	6	6	7	9
Sum fewest rank diff	11	28	*12	19	23	30	*42	*41	*39	*41	*74	†68
5 percent level	4	15	15	18	15	15	42	49	42	42	75	124
1 percent level	0	7	7	10	7	7	31	35	31	31	56	96

*Significant at 5 percent level.
†Significant at 1 percent level.

very insignificant improvement. The Rank Method of comparison shows essentially the same results. All this would seem to indicate that there is a bigger and more difficult step in going from the perfect prognostic flow patterns and frontal positions to the actual weather forecast than was heretofore suspected. This is especially true if one considers the generally small fractional advance made from control forecast scores toward "perfection"; i.e. 100 percent for State forecasts, and zero error for actual temperature forecasts.

Although this is a small sample, first-period precipitation results indicate that short-period (less than 24 hours) prognostic charts of this type are of questionable value to the forecaster for precipitation forecasting under the conditions of this test. Apparently moisture, stability, vertical motion, and probably other types of prognostic charts are also needed in order to significantly improve short-period precipitation forecasts.

However, it does not seem plausible for the meteorologist to follow the exact statistical line of reasoning by rejecting any improvement that does not come up to the 5 percent level of significance, for even at the 10 percent or 20 percent level, it might be held that there is a fairly strong indication of effective improvement from the meteorological point of view.

Since this experiment was completed, the National Meteorological Center has begun transmitting forecasts of vertical motion, precipitation, temperature change, etc., which should be of considerable help to the forecaster.

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SOIL TEMPERATURES AT CAPE HALLETT, ANTARCTICA, 1958

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ABSTRACT

Soil temperatures at 10- and 50-cm. levels were obtained at Cape Hallett from April through December 1958. The instrumentation used is described and graphs and tables of the results obtained are presented.

1. INTRODUCTION

Hallett is one of the few Antarctic stations not located on a snow field. It was believed, therefore that a sampling of subsurface temperatures there would add to the general geophysical knowledge of Antarctica. During 1958, soil temperatures were recorded at depths of 10 and 50 cm. at Cape Hallett, Antarctica. A third level, at 100 cm., was contemplated and a thermohm installed. Unfortunately, bulldozing operations severed the lead-in cable and covered it with compacted fill. The break was not noticed until it was too late for salvage operations.

The Cape Hallett station, operated jointly by New Zealand and the United States during the IGY, is located on a sandy and rocky spit jutting westward from the headland that comprises Cape Hallett (fig. 1). This headland is the southern terminus of Moubray Bay, an extension of the Ross Sea. The spit, which comprises about 40 acres, extends westward from the cape into Hallett Bay in a broad, comma-like configuration. Highest elevation above mean sea level is approximately 15 feet, located close to the northern and western shore line. The main camp buildings are located on this high ground (see fig. 2).

The soil of the spit is sandy with a plentiful supply of rocks and pebbles. The entire area is a penguin rookery and it can be assumed that the soil also consists of consolidated penguin carcasses. It is regretted that a soil analysis is not available for inclusion with this report.

2. INSTRUMENTATION

Figure 3 is a schematic of the instrument complex and shows the relative positions of the various meteorological instruments. The thermohms were placed horizontally in a small, shallow pit. Singer and Brown [1] placed their thermohms vertically, otherwise the installation is similar. Care was taken to replace material in the order in which it had been before. Cable from the thermohms to the recorder was of the lead shielded type and necessary junctions were soldered and insulated.

The primary function of the recording device available, a Leeds and Northrup single-point, curve-drawing recorder, was to measure ambient air temperature. A three-pole switch was installed, permitting air temperature to be recorded continuously except for switching to obtain soil temperatures at standard synoptic observation times.

To establish recorder reliability, the check coil provided with the instrument was inserted periodically. The balance, at −80° F., was obtained at the right-hand edge of the trace. When outside temperatures permitted, the air temperature thermohm was inserted into a bath of water and ice and the temperature noted. The right-

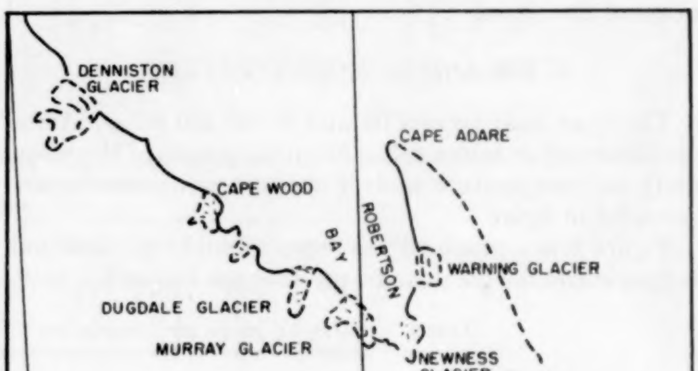

FIGURE 1.—Map of Cape Hallett area, Antarctica.

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FIGURE 2.—View from eastern hills of sandspit on which Hallett station is located. Camp buildings can be seen in the center, Mount Herschel in the background.

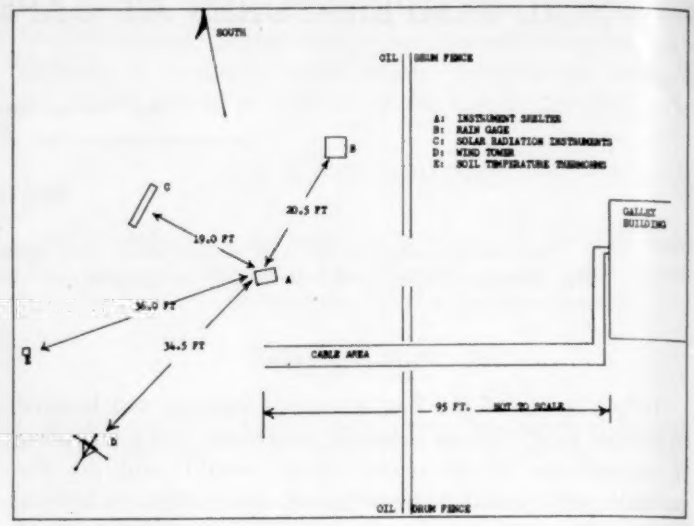

FIGURE 3.—Plan showing location of meteorological instruments at Hallett station, 1958.

hand edge of the trace indicated 32.0°. It was assumed that the readings were similarly accurate over the entire range of the recorder.

3. AIR AND SOIL TEMPERATURES

The mean daily air and 10- and 50-cm. soil temperatures are displayed in tables 1–3. Monthly graphs of the mean daily air temperature and of the soil temperatures are provided in figure 4.

Figure 5 is a graph of the mean monthly air and soil temperatures for the period April through December 1958.

Examination of the two soil temperature traces in figure 5 reveals two differing values for the month of August. The warmer of the mean temperatures is for the period prior to removal of the accumulated snow drift over the thermohm installation. Beginning around the end of March, drifting and falling snow began to accumulate. Rate of accumulation was sporadic, however, depending on storm frequency and intensity. The drifts increased gradually; each storm added several inches followed by a period when the depth was relatively constant.

TABLE 1.—*Monthly mean air temperature (°F.) Hallett, Antarctica, April–December 1958.*

	1958								
	April	May	June	July	August	September	October	November	December
1	11.5	−0.5	−10.5	−3.0	−1.0	−11.0	−12.0	2.5	21.5
2	13.5	−6.5	−10.0	0.5	−8.0	−22.0	−10.5	2.0	18.5
3	10.5	−11.5	−14.0	−8.0	−9.5	−26.0	−15.0	1.0	20.5
4	10.5	−9.0	−23.0	−20.0	−7.5	−26.0	−24.0	9.5	22.0
5	12.0	−3.0	−13.0	−27.5	−8.5	−27.0	−10.0	13.0	20.0
6	13.5	−4.5	−4.5	−25.5	−18.0	−21.5	−4.0	11.5	18.5
7	13.5	−5.5	−11.5	−20.5	−13.0	−21.5	−3.5	12.5	24.5
8	14.5	3.5	−9.0	−25.0	−16.0	−25.5	−5.0	15.5	24.5
9	12.5	−7.0	−13.5	−32.0	−21.0	−27.0	−0.5	15.5	25.0
10	19.0	−11.5	−9.5	−31.5	−17.0	−21.0	−1.0	10.0	23.0
11	19.0	−13.0	−14.0	−18.5	−8.0	−23.0	6.0	15.5	22.0
12	12.0	−14.0	−11.5	−18.0	1.5	−24.0	1.5	17.0	24.5
13	4.0	−15.5	2.0	−20.0	10.0	−17.0	−2.5	19.0	23.5
14	6.5	−13.5	5.0	−16.0	−3.5	−19.0	−4.0	20.5	30.5
15	8.5	−18.0	1.0	−23.0	−16.0	−18.0	−2.5	18.0	30.5
16	1.0	−7.0	−3.5	−30.0	−16.5	−7.5	−6.5	22.5	29.0
17	−4.5	−2.5	−2.5	−18.0	−15.5	−12.5	0.5	19.0	28.5
18	−9.5	−7.5	−5.5	−15.0	−12.0	−15.0	−6.5	16.5	27.5
19	−9.0	−7.0	−11.0	−25.0	−11.0	1.5	−10.0	20.0	26.5
20	−1.5	−8.5	−17.5	−22.0	−21.5	−10.5	−11.5	17.5	26.5
21	−1.5	−18.5	−20.5	−22.5	−21.5	−21.0	−11.5	17.5	26.5
22	−1.0	−19.0	−27.0	−25.0	−32.0	−7.5	0.0	17.5	26.0
23	2.0	−23.5	−17.5	−27.5	−29.5	−4.5	2.5	17.0	28.0
24	9.0	−21.5	−8.0	−26.5	−16.0	−3.5	8.5	16.5	29.0
25	9.0	−23.0	−9.0	−19.0	−11.5	−3.5	9.5	22.5	31.5
26	0.5	−17.0	−12.0	−20.5	−19.5	−7.5	4.5	21.5	30.0
27	2.0	−15.5	−15.5	−27.0	−14.0	−5.5	6.0	19.5	27.0
28	7.5	−18.0	−4.0	−26.5	−14.0	−6.5	14.5	17.0	29.5
29	2.5	−5.0	9.5	−5.5	−20.5	−4.5	13.5	22.0	28.5
30	−5.5	−5.0	3.5	5.5	−21.0	−8.0	12.0	22.0	28.0
31		−17.5		−1.0	−12.5		7.5		27.0
Sums	182.0	−345.5	−276.5	−593.5	−424.0	−445.3	−55.5	471.5	798.0
Means	6.1	−11.1	−9.2	−19.2	−13.7	−14.9	−1.8	15.7	25.7

Table 2.—*Monthly mean 10-cm. soil temperature (°F.), Hallett, Antarctica, April–December 1958.*

	1958								
	April	May	June	July	August	September	October	November	December
1		2.6	−14.7	−1.2	−5.3	−13.8	−16.8	1.6	29.2
2		1.3	−10.2	−0.5	−5.3	−20.1	−16.4	0.5	29.8
3		−2.5	−10.0	0.1	−5.1	−25.1	−17.7	−1.4	30.7
4		−3.2	−11.7	0.2	−5.0	−27.7	−21.3	−0.8	31.3
5		0.1	−10.3	0.5	−5.0	−27.6	−19.3	0.3	32.2
6		0.6	−8.4	1.3	−4.8	−26.1	−14.3	0.9	34.9
7		0.6	−7.1	0.6		−25.6	−12.5	2.1	32.9
8		0.8	−7.1	0.2		−27.5	−10.7	3.5	33.9
9		−1.9	−7.6	0.0		−27.4	−9.4	4.4	34.9
10		−3.8	−8.1	−0.6		−24.4	−7.9	4.1	36.6
11		−3.6	−8.7	−1.3		−27.2	−0.9	3.8	36.8
12		−4.8	−9.8	−1.6		−27.8	−4.8	4.6	36.9
13		−8.3	−4.9	−2.1		−22.5	−7.2	5.4	39.5
14		−10.3	−1.8	−2.4		−21.1	−6.3	6.9	39.8
15		−11.3	−1.2	−2.7		−21.0	−6.2	8.2	43.3
16		−10.5	−0.9	−2.9		−15.0	−9.5	9.8	43.8
17		−8.7	−1.0	−3.0		−15.5	−4.3	10.6	44.9
18		−6.5	−1.8	−3.1		−19.7	−2.6	11.0	41.5
19		−7.7	−1.0	−3.3		−12.3	−6.7	11.2	37.9
20		−9.6	−1.1	−2.9		−9.9	−8.2	11.1	34.3
21	0.1	−11.6	−1.1	−3.0		−19.4	−8.5	11.1	33.2
22	0.4	−12.8	−1.5	−3.1	−27.1	−9.8	−4.8	11.9	34.2
23	2.3	−15.2	−1.8	−3.6	−28.8	−6.7	−2.4	22.3	36.8
24	4.3	−16.4	−2.6	−4.1	−22.0	−10.4	−0.5	32.0	37.5
25	3.2	−22.0	−3.0	−4.3	−17.0	−7.6	1.4	32.1	37.1
26	3.0	−18.2	−2.9	−4.7	−19.3	−13.4	3.6	32.0	37.7
27	0.9	−15.3	−2.7	−4.7	−18.6	−9.8	1.2	31.9	37.0
28	5.3	−16.5	−2.7	−5.6	−17.6	−12.3	4.9	31.6	37.6
29	5.7	−14.3	−2.6	−5.0	−21.5	−11.1	3.9	30.0	36.1
30	2.7	−9.7	−1.9	−5.7	−22.8	−14.1	2.3	29.4	33.4
31		−13.6		−5.1	−16.9		2.2		31.6
Sums	27.9	−252.3	−149.9	−73.6	−211.6	−551.9	−199.7	−362.1	1117.3
Means	2.8	−8.1	−5.0	−2.4	−21.2	−18.4	−6.4	12.1	36.0

Table 3.—*Monthly mean 50-cm. soil temperature (°F.), Hallett Antarctica, April–December 1958.*

	1958								
	April	May	June	July	August	September	October	November	December
1		8.9	−2.7	0.0	−1.4	−10.8	−9.6	−0.8	22.9
2		8.8	−2.9	−0.2	−1.9	−10.4	−12.1	−0.4	23.0
3		8.2	−2.8	0.8	−1.8	−11.1	−11.8	−0.9	23.7
4		7.8	−2.6	0.8	−1.9	−12.2	−10.9	−1.2	24.2
5		7.0	−2.9	0.8	−2.2	−13.2	−11.2	−1.1	24.7
6		7.2	−2.9	1.1	−2.5	−13.8	−11.1	−0.7	25.3
7		7.2	−2.5	1.6	−11.7*	−14.0	−10.3	−0.3	25.8
8		7.1	−2.2	1.6	−2.0*	−14.2	−9.6	−0.1	26.0
9		6.2	−2.1	1.7		−14.7	−9.1	0.5	26.3
10		6.5	−2.2	1.7		−14.8	−8.7	1.3	26.5
11		6.1	−2.4	1.0		−14.9	−7.5	1.6	26.7
12		5.7	−2.5	1.4		−15.3	−6.3	1.8	27.2
13		5.2	−2.1	1.2		−15.4	−6.4	2.3	27.3
14		4.4	−2.2	1.0		−14.7	−6.6	2.9	27.7
15		3.5	−1.1	0.9		−14.5	−6.2	3.4	28.0
16		2.9	−0.8	0.7		−13.5	−4.9	4.2	28.1
17		2.3	−0.6	0.3		−12.9	−6.3	5.1	28.9
18		2.2	−0.1	0.1		−12.8	−5.7	5.8	29.0
19		2.0	0.1	0.1		−12.8	−5.3	6.2	29.1
20		1.9	0.0	0.6		−11.4	−5.8	6.8	29.4
21	8.4	1.6	0.1	0.6		−11.1	−6.2	6.9	29.1
22	8.5	1.0	0.3	0.3	−9.1	−11.7	−6.1	7.2	29.0
23	8.1	0.3	0.2	−0.1	−10.5	−10.2	−5.6	15.7	29.0
24	8.8	−0.4	0.4	−0.6	−11.3	−9.0	−4.8	21.2	29.1
25	9.1	−1.2	0.3	−0.8	−11.1	−9.1	−3.7	22.4	29.3
26	8.9	−2.0	0.2	−0.6	−10.4	−8.9	−2.9	22.8	29.4
27	9.0	−2.2	0.6	−1.2	−10.7	−9.2	−2.6	23.0	29.4
28	8.8	−2.5	0.3	−1.0	−10.7	−9.0	−2.1	22.9	29.6
29	8.8	−3.0	0.3	−1.1	−10.3	−9.1	−1.2	23.1	29.8
30	9.0	−2.9	0.2	−1.1	−11.2	−9.4	−0.9	23.2	29.9
31		−2.4		−1.4	−11.3		−0.8		29.9
Sums	87.4	97.4	−34.6	9.2	−106.6†	−364.1	−202.0	225.6	853.3
Means	8.7	3.1	−1.2	0.3	−10.7†	−12.1	−6.5	7.5	27.5

*Sum and mean of first 6 days.
†Sum and mean of last 10 days.

However, the largest accumulation of snow occurred in June, the stormiest month according to Benes [2].

The decision to bulldoze the drifts was made early in August, after several days of readings were obtained. After the 4- to 5-foot drifts were removed, a sharp drop in soil temperatures was observed at both levels. At the 10-cm. level this temperature change, on a monthly mean basis, was about 16° F. At the 50-cm. level, the temperature change downward was about 8°.

It is interesting to contrast soil temperatures before

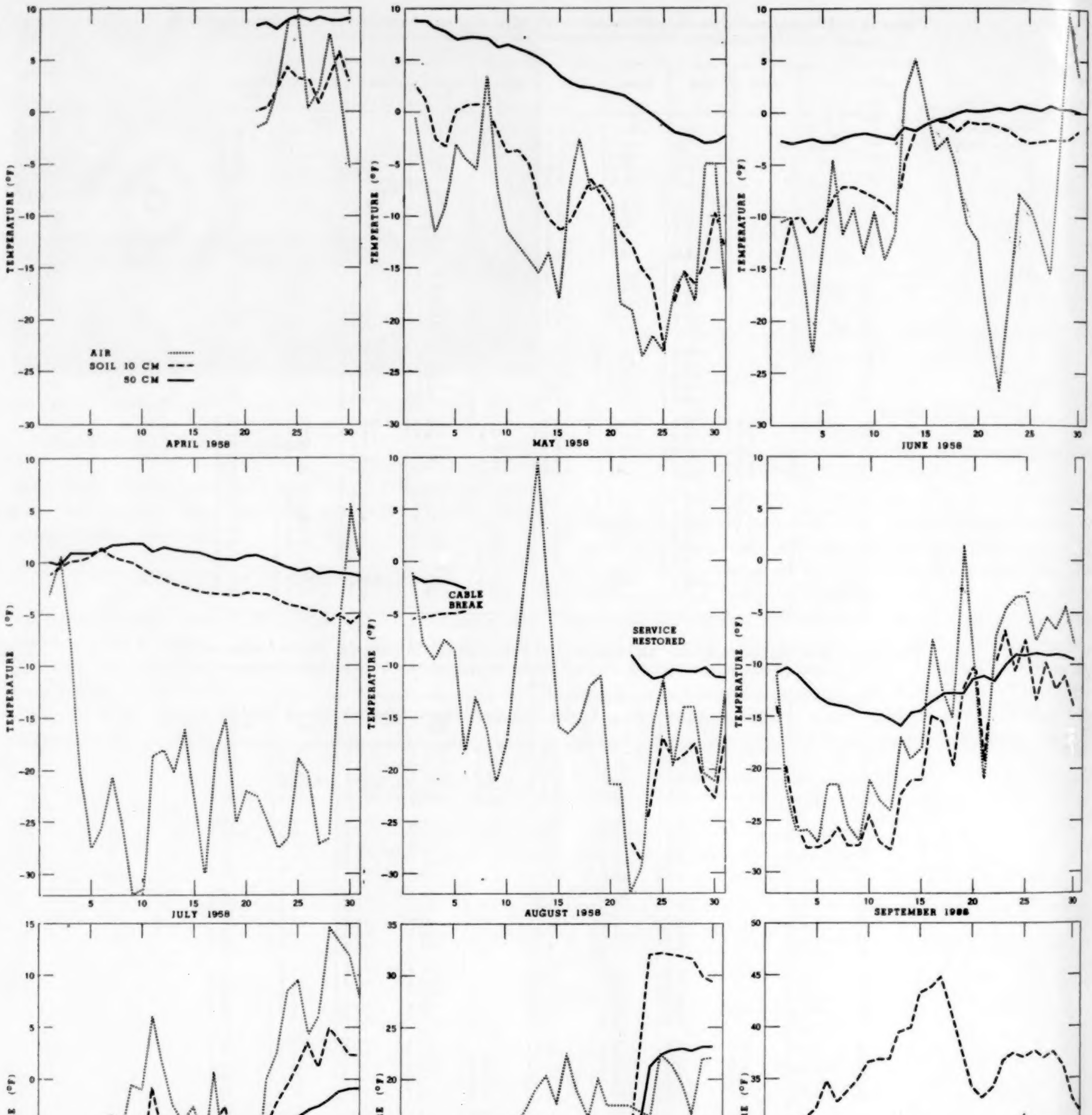

FIGURE 4.—Daily mean temperatures, both air and soil, at Hallett station, Antarctica, April–December 1958.

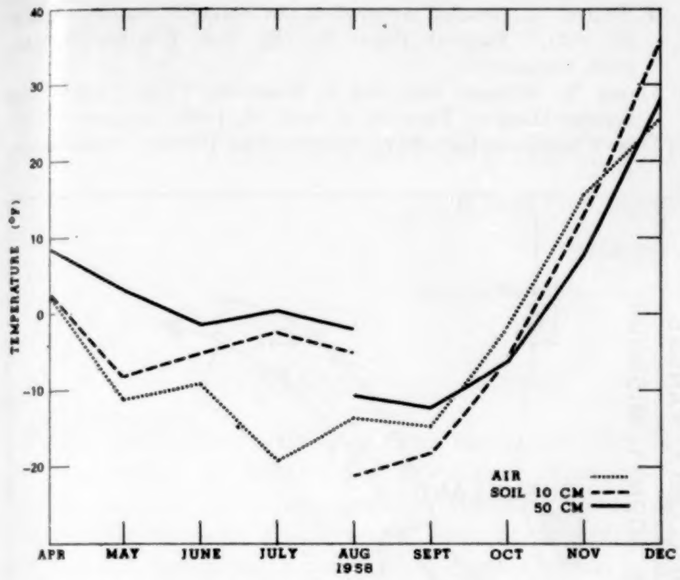

FIGURE 5.—Monthly mean temperatures, air and soil, Hallett station, Antarctica, April–December 1958.

and after drift removal. Under the deep snow cover, particularly in July (see July graph, fig. 4), while air temperature was fluctuating widely and erratically, soil temperatures were decreasing at a gradual rate. With the removal of the insulating snow, mean daily soil temperatures, particularly at the 10-cm. level, followed closely the fluctuations of air temperature. During most of the measurement period, the soil temperature curves followed the air temperature curve. Largest deviation occurred in July and the greatest warming took place at the 10-cm. depth. From September on, the trend for air and subsurface temperatures was upward; the mean monthly air and soil temperature traces then displayed a nearly linear relationship.

The tremendous increase of soil temperatures on November 22 and 23 (see November graph, fig. 4) is attributed, at least in part, to a large pool of snow melt that covered a large area and then rapidly drained into the subsoil. After this upward surge of soil temperature, the daily mean for both levels generally remained higher than the daily mean air temperature.

4. CONCLUDING REMARKS

This project was an interesting sideline to the regularly programmed schedule of observations and necessitated some improvisation to secure accurate data. It provides, in general, some knowledge of the temperature regime to be found in Antarctic soil. In addition, a first approximation of the depth of permafrost in the Cape Hallett area is provided. With data available on solar radiation, these temperatures may provide extra material for heat budget studies.

ACKNOWLEDGMENTS

The author wishes to thank Aerographers Keeler, Highlands, and Garczynski for the dial switching every six hours, and Electronic Technician Vanatta for the installation of the three-pole switch.

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Weather Note

UNUSUALLY WIDE TORNADO PATH

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[Manuscript received May 6, 1960]

On April 15, 1960, between the hours of 1730 and 1830 CST a tornado traversed portions of Miami County, Kansas, and Cass County, Missouri. The purpose of this note is to describe some features of the storm path revealed by a survey of the damaged area made on April 16 and 18, 1960. The survey was accomplished by traversing all roads in the area and observing the location of damage patterns relative to the roads.

The path of the storm is shown in figure 1 and some comments on specific observations along the path are given in the caption. Three noteworthy features of the overall 14-mile-long path are: (1) its meanderings, as shown by a range of directions from 210 to 280 degrees; (2) its apparent production by at least two storms, separated from each other by a distance of ¾ to 1¾ miles with an overlap from west to east of about 2 miles; and (3) its unusual width, ranging up to a mile in the portion made by the first storm, up to 1.2 miles in the portion made by the second storm, and up to 1.4 miles across the overlapped area.

That the unusual width of the storm path resulted from more than one tornado was borne out by the testimony of several eyewitnesses who reported more than one funnel. Moreover, the width of the path, the general absence of total destruction, the abrupt shifting of winds at several points, and the discontinuity line between northerly and southwesterly winds along portions of the path suggest a circulation system larger than the individual tornado funnel. It appears that this storm may have been of the "tornado cyclone" type described by Brooks [1], the micro-cyclone type described by Williams [2], or the rotating mother cloud-tornado system described by Fujita [3].

A fuller report on the results of this storm survey is available in manuscript form [4].

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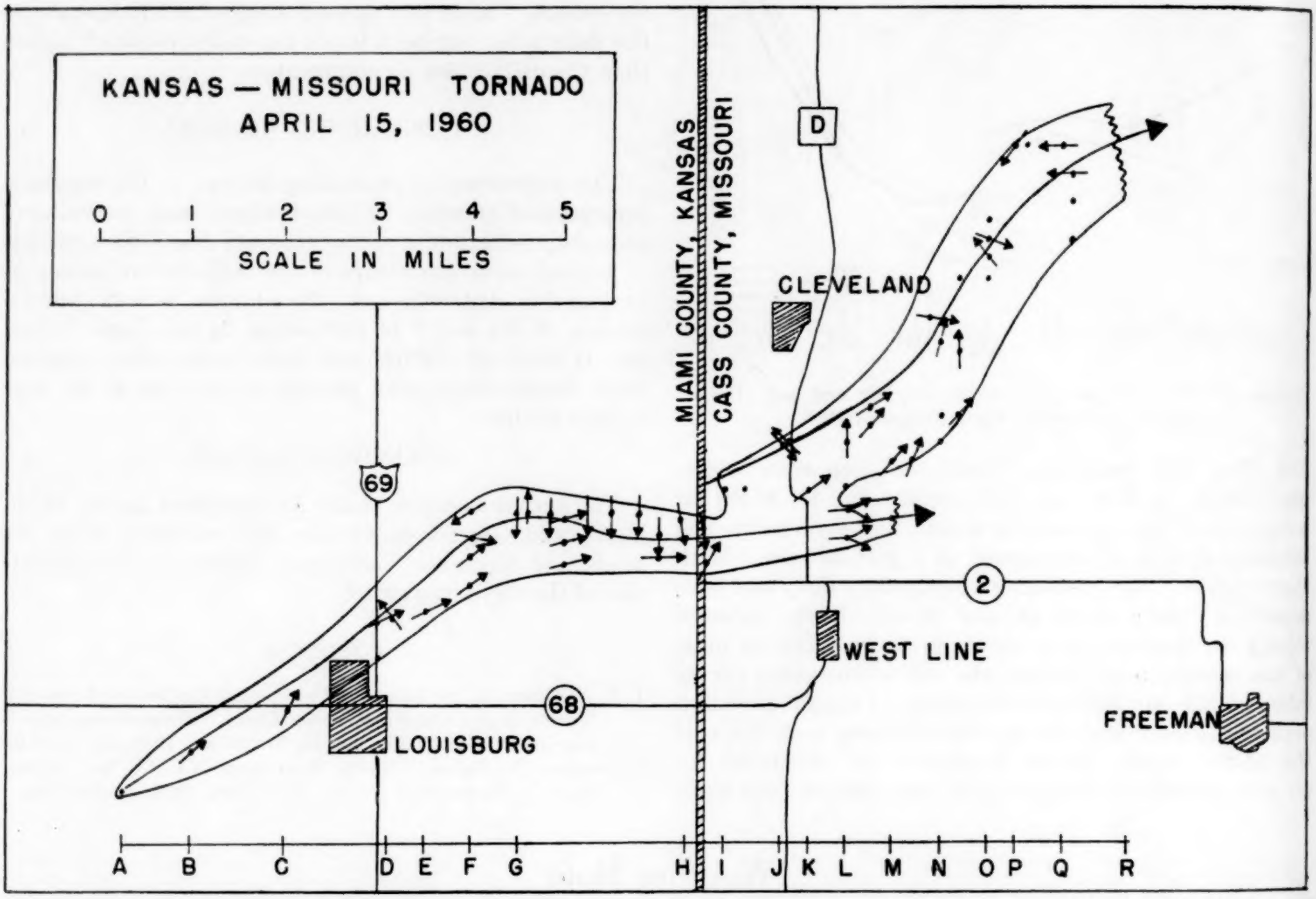

FIGURE 1.—Plot of the path of the storm of April 15, 1960. Damage was specifically noted at points marked by dots. If direction of damaging wind was apparent, it is indicated by a short arrow. Axes of the two overlapping storm paths are indicated by the long arrows. Specific observations, keyed according to the letters along the scale at bottom of figure, were:

A—Very minor damage. Apparent beginning of the first tornado.

B—Minor damage. Chickenhouse tipped over.

C—Telephone lines damaged. Highway Department building destroyed.

D—Major damage to farm buildings. First evidence of other than southwesterly winds. Damage caused first by southeasterly, then by westerly winds in time interval of a minute or longer. A threshing machine tipped over to the west. Debris of one outbuilding was carried to the northwest. House windows and doors blown open from within, suggesting pressure differential. Electric clock stopped at 1750 CST. Three funnels observed, the last two merging into one.

E—Damage to a north-south line of trees.

F—Southwesterly winds to right, northwesterly winds to left of path.

G—Major damage to farmstead; damage from southerly wind preceded damage from northerly wind. Storm track reached width of 1 mile, and direction turned abruptly from southwest to east.

G to H—Definite discontinuity between damage due to northerly winds and southwesterly to westerly winds. Track of storm from west to east.

I—Apparent beginning of second tornado ¾ mile north of track of first tornado.

J—Along track of second tornado, wind shifted from southeasterly to northwesterly with damage from both directions.

K—Major damage to trees by winds primarily from southwest, apparently part of circulation of second tornado.

I to K—Virtually no damage along path of first tornado.

L—West wind damage along path of first tornado but with marked scattering of debris to southeast through northeast. The overlapping of the two paths gave total width of 1.4 miles.

M—Apparent end of first tornado; easternmost point of damage.

L to N—Widening of second tornado path. General southerly to southwesterly wind.

O—Definite discontinuity between southeasterly and northwesterly winds.

P—Northeasterly wind on extreme left edge of path.

Q—Easterly winds in northern portion of path; wind direction not apparent in southern portion. Path reached width of 1.2 miles.

R—Apparent end of second tornado; easterly winds.

THE WEATHER AND CIRCULATION OF JUNE 1960

A Hot Dry Month in the Southwest

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1. INTRODUCTION

In the southwestern United States the month of June 1960 was one of the hottest and driest ever experienced, even in that normally hot and dry region. Numerous new records for high temperature, amount of sunshine, and rainfall deficit were established from California to Texas. The hot spot of the nation was Yuma, Ariz., where the monthly average of 92.3° F. was the highest ever recorded there for June, and the maximum temperature, which averaged 108.8° F. for the period, exceeded 100° each day and reached 115° on several occasions. By contrast the East was cool and wet, following a trend which characterized May as well as the spring season as a whole. The associated circulation pattern featured westerlies flowing across the northern United States with a trough of broad cyclonic curvature in the East. The first tropical storm of the season, though small and of only moderate intensity, brought flood rains to southeastern Texas.

2. THE MEAN CIRCULATION

The mean circulation pattern at 700 mb. for June 1960 (fig. 1) was dominated by a narrow band of relatively fast westerlies extending in an unbroken sweep around the Northern Hemisphere. As a result of the small amplitude of the planetary waves, the latitude of the axis of maximum westerlies (fig. 2) varied less than 10° along its entire course from Japan across the Western Hemisphere to the British Isles. The accompanying subtropical Highs over both oceans were similarly zonal in nature with centers near their normal locations. As a consequence, departures from normal height in those areas were quite small. Broad cyclonic curvature characterized the central Pacific trough and its downstream counterpart over the United States. The wavelength between these two systems was long by summertime standards and appears to have been sustained by the stronger than normal westerly circulation (fig. 2). Thus, the trough normally active along the United States west coast was entirely absent at middle latitudes, and positive departures from normal dominated the whole region. In this respect, the June pattern differed sharply from that of May when the trough was very vigorous [1]. The filling of this trough (anomalous 700-mb. heights rose over 300 ft. off the Washington-Oregon coast in conjunction with this change) led to a temperature reversal in the West from a relatively cool May to a June heat wave. The small-amplitude westerly flow across the northern tier of States favored the progression of several daily cyclones roughly along a zonal course across the country (see tracks in Chart X of [2]). Some of these storms passed sufficiently close to the Gulf of Mexico to draw in a supply of moisture and produce heavy rainfall over much of the East.

Over northern Canada a system of larger amplitude prevailed with a ridge of a blocking type in the far northwest and a vigorous low center over the Davis Strait. The blocking ridge accounted for the largest departure from normal (+240 ft.) observed on the mean map for the month. Blocking was also active during the previous month [1], though centered mainly in the Maritime Provinces of Canada in that instance. A vestige thereof continued into June and was reflected in the anomaly center of +120 ft. off the Newfoundland coast. However, the principal seat of blocking migrated northwestward early in June and became well entrenched northward from Hudson Bay.

Over Eurasia departures from normal were remarkably small, even for a June map, and trough and ridge positions agreed well with their normal locations. Height departures were generally positive and the flow difluent over Europe, reflecting the retrogression of a weak blocking ridge which was active mainly over Russia during the first half-month and over the British Isles during the latter half.

3. TROPICAL STORM ACTIVITY

The first tropical storm of the season moved ashore just south of Corpus Christi, Tex. during the early morning of June 24 and proceeded to move very slowly north-northeastward across eastern Texas during the next two days. The attendant prolonged period of torrential rains, which resulted in severe flood conditions along most streams in southeastern Texas, was described by Dunham [3].

While tropical storms are not frequent over the Gulf of Mexico during June, they have occurred on several occasions, and some, such as Beulah in 1959, Audrey in 1957, and Alice in 1954, have reached hurricane proportions.

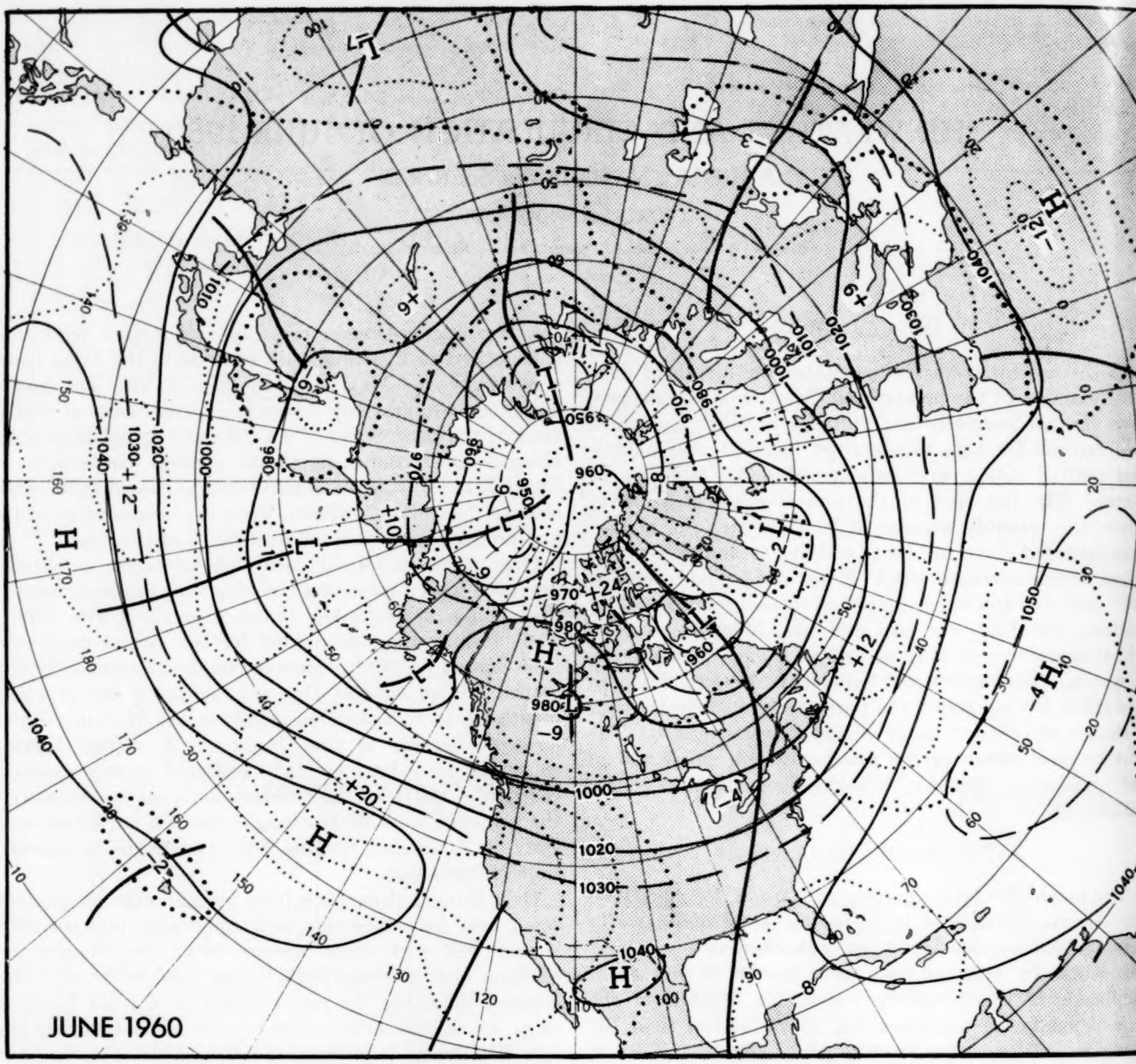

FIGURE 1.—Mean 700-mb. contours (solid) and height departures from normal (dotted), both in tens of feet, for June 1960. Blocking over northern Canada and a more southerly than normal band of westerlies with broad cyclonic curvature composed the principal circulation features over North America.

A number of these have developed in a manner described by Riehl [4], in which: (A) a westerly trough of large amplitude extends well into the Tropics, and (B) the southern portion shears from the parent trough and retrogrades. Oftentimes the tropical portions of the sheared waves are observed to weaken as they pass to the south of the subtropical anticyclone and subsequently to reintensify upon emergence on the southwestern side of the High. An example of this sequence was described by Green [5] in terms of 5-day mean maps. The storm which occurred this June developed in a closely analogous manner, and a series of 5-day mean maps has been chosen to illustrate this evolution (fig. 3).

Figure 3A represents the 700-mb. 5-day mean flow pattern for June 14–18. A deep full-latitude trough extended from northeastern Canada through the subtropical ridge into the Gulf of Mexico. In fact, this trough and the one in the Atlantic were the only trough systems in the Western Hemisphere which were able to penetrate appreciably into the Tropics. Elsewhere the subtropical anticyclonic belt was well developed with little or no meridional exchange between the westerly and trade wind

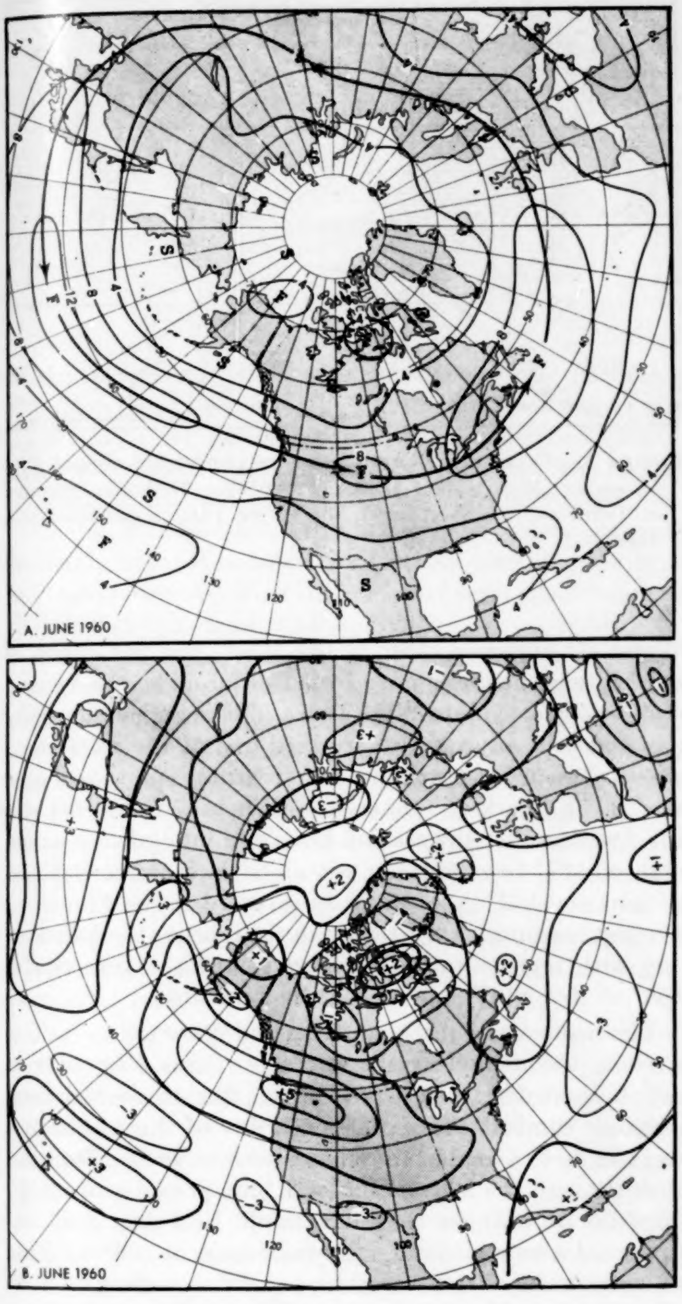

FIGURE 2.—(A) Mean 700-mb. isotachs and (B) their departure from monthly normal wind speed (both in meters per second) for June 1960. Solid arrows in (A) indicate axes of primary west wind maxima. The westerlies were stronger than normal over most of the Western Hemisphere and of relatively small amplitude.

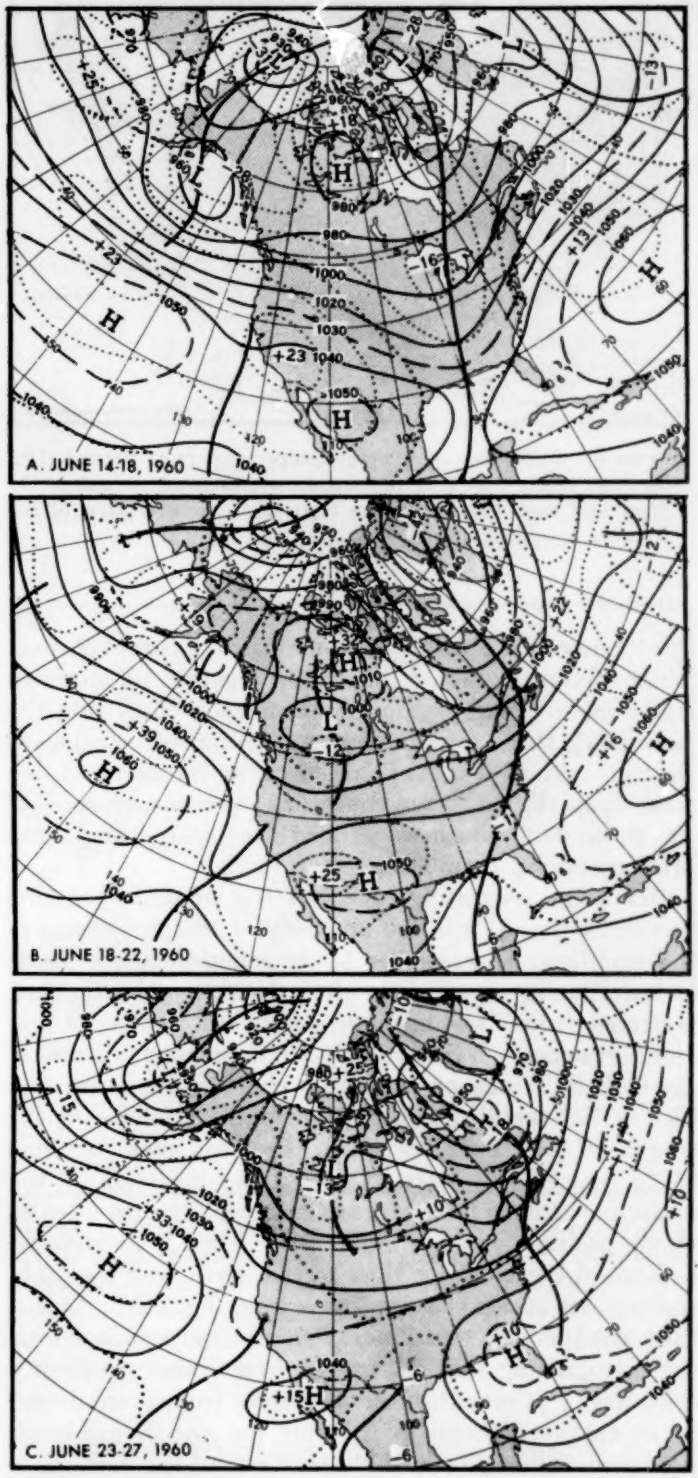

FIGURE 3.—Five-day mean 700-mb. contours (solid) and height departures from normal (dotted), both in tens of feet, for (A) June 14–18, (B) June 18–22, and (C) June 23–27, 1960. The deep trough in the Mississippi Valley on (A) assumed a strong positive tilt on (B) and sheared on (C) as the southern portion retrograded to central Texas.

systems. In this respect the flow of this 5-day period closely resembled that of the month as a whole (fig. 1), as indeed was the case with most other circulation elements including the blocking High over northwestern Canada.

During the ensuing period (fig. 3B), the United States trough showed a tendency to shear, as it continued to make eastward progress in the north but stalled in the south. During this phase, as the subtropical ridge bridged across to the north, the sea level tropical storm center became weak and poorly defined so that it was difficult to

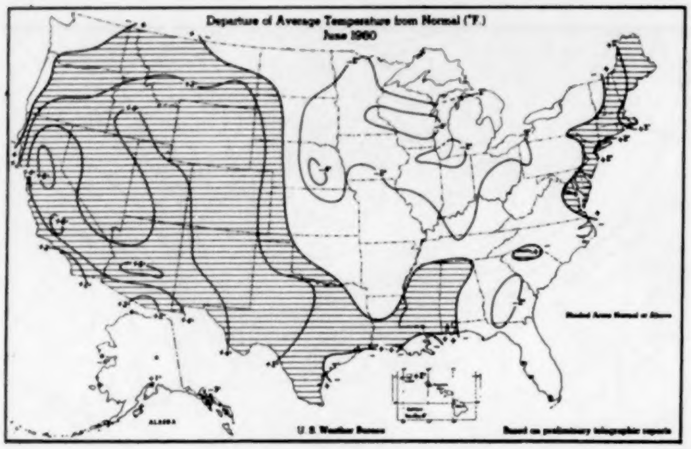

FIGURE 4.—Departure of average temperature from normal (°F.) for June 1960. The June pattern showed unusual warmth in the West and cool weather in the East with the exception of the Northeast. (From [6]).

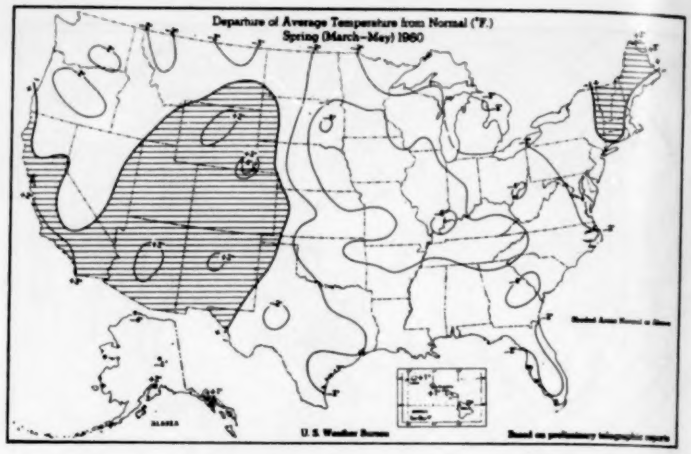

FIGURE 5.—Departure of average temperature from normal (°F.) for spring (March-May) 1960. (From [6]). With the exception of Texas and the Northwest, the spring pattern persisted into June.

trace across the central Gulf of Mexico. However, during the following period (fig. 3C) it regained its intensity and became a well organized storm upon entry into the continent, then retrograded and recurved northward through eastern Texas. The effect, as far as the 5-day mean map (fig. 3C) was concerned, was retrogression of the sheared off southern part of the mean trough into Mexico and southern Texas.

One other interesting aspect of the circulation during this series (fig. 3) was the tendency of trough systems in the mid-latitude westerlies to be independent of those at lower latitudes. This is often the case when the flow is strongly zonal, and has been noted on a number of previous occasions. As an example, the depression centered in the Gulf of Alaska on the initial chart of the series (fig. 3A), moved rapidly eastward and joined briefly with the trough off Lower California on the mean map for June 16–20 (not shown), only to sever this connection on the mean map 2 days later and advance rapidly into Canada to the position shown in figure 3B. Then it decelerated because of the blocking High to the north, and was only slightly east of this position 5 days later (fig. 3C). At this time, the juncture was almost, but not quite, made with the retrograding tropical trough over Texas previously considered. Thereafter the northern trough continued on an eastward course and, before the month was over, combined with a low-latitude remnant of the east coast trough which had been left behind when the northern portion of the latter similarly sheared and moved eastward. Thus, during this period, this system, originally over the Gulf of Alaska, joined with two low-latitude troughs and by-passed a third as it journeyed eastward.

4. TEMPERATURE

The extremely hot dry weather in the Southwest was the most noteworthy weather phenomenon during June. Warm air occupied most of the West, but the region of most intense heat extended from California across Arizona and New Mexico into West Texas. This region, normally hot and arid anyway, experienced one of the worst heat waves of record as maximum temperatures soared well over the 100° F. mark on numerous occasions. California was the first to suffer the searing heat, and on June 2 maxima reached 107° to establish a new all time record at Oakland Airport and 102° to set a new June record at San Francisco. Highest maxima were reached in the interior the following day with representative readings of 109° at Bakersfield, 108° at Red Bluff, and 107° at Sacramento.

The heat wave subsequently spread eastward to include Arizona about mid-month and the Texas-New Mexico region thereafter. At Yuma, Ariz., the maximum temperature climbed above 100° each day of the month and went on up to a torrid 115° on four successive days from the 19th through the 22d. Winslow, Ariz. posted a new high for June of 103° on the 19th; while El Paso, Tex., experienced a new all time daily maximum of 108° on June 18, only to have this value topped by a reading of 109° on June 21.

New records were also set at a number of localities for the month as a whole, and these have been tabulated in table 1 in order of descending departure from normal. The list is headed by Blue Canyon, Calif. where the average temperature was 8.2° above normal. Consequently in an anomalous sense at least, Blue Canyon was the hot spot of the nation.

In the matter of this heat wave, the June temperature distribution differed markedly from that of the preceding May when it was generally cool in the West. It has already been noted that the west coast trough was deep and vigorous during May but very weak and confined to the lower latitudes in June. Thus, the much warmer weather of June may be attributed to the enfeeblement

Table 1.—*New record average temperatures for June established during 1960.*

	Monthly average (° F.)	Departure from normal (° F.)
Blue Canyon, Calif	67.2	+8.2
Sandberg, Calif	72.8	+8.0
Bakersfield, Calif	83.7	+6.8
Red Bluff, Calif	82.4	+6.4
Phoenix, Ariz	90.0	+6.1
Winslow, Ariz	76.4	+5.0
El Paso, Tex	85.0	+4.8
Yuma, Ariz	92.3	+4.5
Las Vegas, Nev	87.4	+3.8

of this trough and the virtual absence of any outbreaks of cooler Pacific air into the Southwest in any strength. As a result, dry air of continental characteristics dominated the region, the influx of solar radiation was largely unimpeded, and hot desertlike conditions prevailed.

In the Northwest on the other hand where stronger westerlies favored occasional intrusions of cooler maritime air, temperatures were milder and averaged near or slightly below normal for the month.

In the East, the generally cool regime which prevailed was in many respects a continuation of the pattern of the previous month as well as that of the spring season. This is well illustrated by comparison of figure 4 with figure 5 and also figure 4A of [1]. Remarkably close agreement can be noted over the extensive region of negative anomalies covering the East-Central States as well as the warmer than normal areas in the far Northeast and in the Rocky Mountains. The strong May to June reversal of temperature previously described in connection with the western heat wave was limited therefore to the far Southwest and Texas.

The coldest weather with respect to normal was centered in Wisconsin, where the anomaly for the month of June was −4° F. over the central portion of the State. The cool conditions were not nearly as intense, however, as the hot spell in the Southwest (coolest anomaly −4.4° F. at Minneapolis, compared to warmest +8.2 at Blue Canyon), but they were also persistent. Minneapolis, for example, recorded below normal average temperatures each week of the month. A few new low temperatures for the dates were registered on the 3d at Burlington, Vt., with 36° F., and on the 18th at Toledo, Ohio, with 43° F., and at Louisville and Lexington, Ky., with 48° and 53° respectively.

Circulation features (fig. 1) which had a bearing on the cool weather in the East were: The blocking in Canada with the associated westerlies displaced southward, the cyclonic curvature of the flow, and below normal 700-mb. height values. Also, the coolest areas corresponded quite well with the rainfall distribution, in line with the well-known summertime correlation between these two quantities.

5. PRECIPITATION

With the exception of the Middle Atlantic and Central

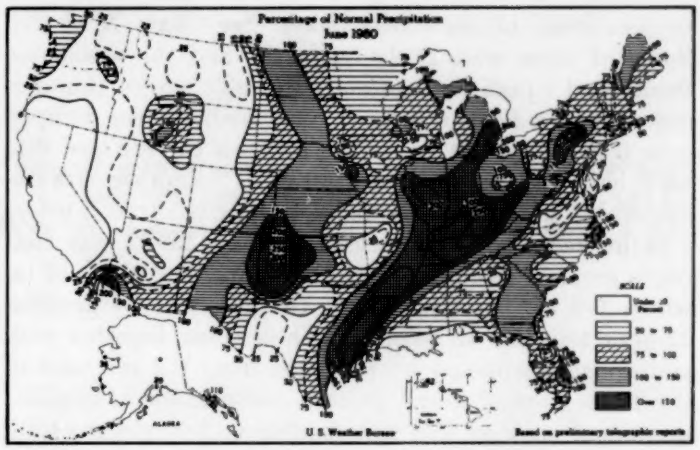

Figure 6.—Percentage of normal precipitation for June 1960. The wet weather which occurred over most regions east of the Continental Divide contrasted sharply with the near drought conditions which developed west of it. (From [6]).

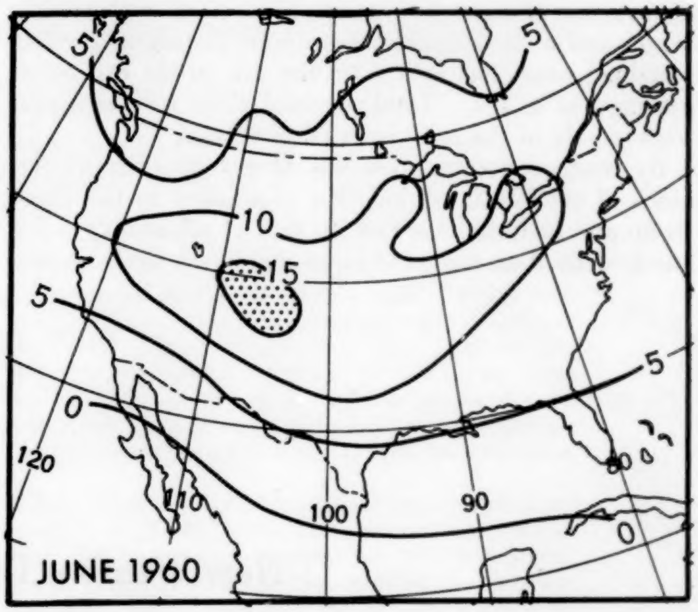

Figure 7.—Number of days in June 1960 with surface fronts of any type (counted within equal area quadrilaterals of 66,000 square nautical miles). All frontal positions taken from *Daily Weather Map*, 1300 EST. The axis of greatest frequency lay east-west across roughly the middle of the country. Several fronts penetrated as far south as the Gulf of Mexico.

Gulf States, precipitation was mostly adequate in the eastern portion of the country (fig. 6). The heaviest rainfall occurred in a band extending from eastern Texas northeastward up the Ohio Valley and into New York State. Much of this, particularly that along the southern portion of this axis, resulted from the tropical storm of June 24–28 described earlier. The remainder appears to have been related primarily to the more southerly than normal storm track along the mean frontal zone shown in figure 7. Several Lows moved along this frontal boundary, passing well south of normal either through

or just south of the Great Lakes (See Chart X of [2]). Some of these were fairly energetic, and the associated fronts and squall lines produced locally severe thunderstorms and a few tornadoes. One such system dumped over 6 in. of rain at Amarillo, Tex., on the 8th and 9th, with hail damage on the latter date. Another was responsible for excessive rains in western Kentucky, where 5.14 in. recorded at Louisville on June 22–23 was that city's greatest 24-hour amount for June, and the 5.12 in. which fell on the morning of the 23d was its greatest 12-hour total for all records. These rains, together with additional downpours on the 28th from the remnant of the Texas tropical storm, plus the contribution of frequent additional showers and thunderstorms, brought the total for the month at Louisville to 10.11 in., a new record for June. New record monthly totals also accumulated at Lexington, Ky., with 11.69 in.; Amarillo, Tex., with 9.85 in.; and Houston, Tex., with 14.66 in.

Precipitation in the Southeast occurred mainly as showers or thundershowers in connection with trailing fronts and a weak-appearing tropical disturbance which remained over that area from the 4th to the 8th before passing out to sea. Total accumulations for the month were mostly in the neighborhood of normal.

By contrast precipitation was almost nonexistent over much of the West. A long list of stations in the Great Basin and in California had no rain at all or only a few hundredths of an inch, and range and forest lands became brown and very dry as the month progressed. Rainfall was also subnormal along the lee areas of the Rockies from central Colorado northward. Strong westerly flow dominated this region, and the drying action of this current as it descended the mountain slopes produced the driest June of record at Great Falls, Kalispell, and Helena in Montana. In Wyoming, the moisture shortage was assuming drought proportions. Typical of this regime was Sheridan, where June was the driest since 1933, and only 3.37 in. of precipitation had fallen this year up to July 1—a deficit of 6.86 inches.

REFERENCES

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New Weather Bureau Publication

Technical Paper No. 20, "Tornado Occurrences in the United States," Washington, D.C., Revised 1960, 71 pp.; for sale by Superintendent of Documents, U.S. Government Printing Office, Washington 25, D.C., Price 45 cents.

This revision of the first edition of *Technical Paper* No. 20 extends the tornado record of 1916 to 1950 to include the years 1951 through 1958.

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